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# FINAL PERFORMANCE REPORT

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# Fate of Earth Microbes on Mars — UV Radiation Effects

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A radiative transfer model is used to quantitatively investigate aspects of the martian ultraviolet radiation environment. Biological action spectra for DNA inactivation are used to estimate biologically effective irradiances for the martian surface under cloudless skies. Although the present-day martian UV flux is similar to early earth and thus may not be a limitation to life in the evolutionary context, it is a constraint to an unadapted biota and will rapidly kill spacecraft-borne microbes not covered by a martian dust layer. Here calculations for loss of microbial viability on the Pathfinder and Polar lander spacecraft are presented and the effects of martian dust on loss of viability are discussed. Details of the radiative transfer model are presented.

## INTRODUCTION

On Mars the lack of a significant ozone layer and the lower total atmospheric pressure than the earth results in an environment with a higher surface flux of ultraviolet radiation. This UV flux has been considered to be a constraint to life (e.g., Sagan and Pollack, 1974). On Archean Earth (3.9-2.5 Ga), during the period before the accumulation of atmospheric oxygen and ozone, life was probably exposed to higher UVB radiation than present-day earth and also UVC radiation (e.g., Sagan 1973, Margulis et al. 1976, Kasting 1993). Many types of organisms, including cyanobacteria, had colonized the Earth (Schopf and Parker 1987, Mojzsis et al. 1996). Thus, based on the similar DNA weighted irradiances calculated for Archean earth and present-day Mars, it has been suggested that even the present-day martian UV flux may not be a limitation to life in the evolutionary context (Cockell, 1998). However, it is in synergy with other extremes such as low temperatures and the lack of liquid water that the environmental stress of UV radiation contributes to the biologically inhospitable nature of the present martian surface (Cockell, 1998) and even the lack of preservation of organics (Stoker and Bullock 1997). Although the martian UV flux may not be limiting in the evolutionary context, the damage will of course be significant for an unadapted present-day terrestrial biota transferred to Mars, and particularly for artificial ecosystems (Cockell and Andrady, 1999).

The present day UV flux at 200, 250, and 300 nm on the martian surface was calculated by Kuhn and Atreya, (1979) for different times of the year. In this report, a theoretical assessment of the UV radiation environment on Mars is presented. Implications for the introduction of terrestrial organisms to the martian surface, relevant to planetary protection concerns are considered.

## CALCULATION OF THE MARTIAN UV RADIATION ENVIRONMENT

### (I) Calculation of UV radiation flux on Mars

The radiation flux that reaches a point on the surface of Mars will depend on a variety of factors such as the presence of cloud cover, atmospheric dust loading, season and latitude (Sagan and Pollack 1974, Kuhn and Atreya 1979). It can be calculated using a radiative transfer model. We assumed a 6mb atmosphere of $CO_2$ with no other significant gaseous constituents. During perihelion when the southern polar cap sublimes, total atmospheric pressure may increase to between 9 and 10mb as was observed during winter solstice at the two Viking landing sites (Hess et al., 1980). Thus, the assumption of a 6mb atmosphere is a typical summer value for most sites on Mars. Neither water or the low levels of atmospheric $O_2$ in the martian atmosphere have significant absorbance in the UV region at martian column abundances. The extraterrestrial solar spectrum is now well defined. High altitude aircraft, balloons and measurements from Spacelab 2 have provided accurate information on the spectrum of the Sun in the near-Earth environment (Aversen et al. 1969, Mentall et al. 1981, Van Hoosier et al. 1987, Nicolet 1989). The radiation incident on the top of the martian atmosphere was calculated from Nicolet, (1989) with an inverse square-law reduction, based on the seasonally-dependent sun-Mars distance and it was input into the radiative transfer model. These UV radiation fluxes correspond to a period of low solar activity in 1985 (Nicolet, 1989).

Direct UV flux was calculated using Beers law. The solar zenith angle was calculated for any given latitude, orbital position and time of day using standard equations (e.g., Haberle et al. 1993). Diffuse UV light was calculated independently of direct flux so that UV radiation on shaded surfaces could be estimated. It was

calculated using a Delta-Eddington approximation which assumes reflection on a Lambertian surface (e.g., Haberle et al. 1993) and is based on the 2-stream model described by Joseph et al. (1976).

UV flux was calculated with a resolution of 2 nm. Dust is also an important factor on Mars. On clear days optical depth can range between 0.1 to 1.0 in the visible (Haberle et al. 1993). Localized dust storms will generate an optical depth of 2.0 and severe dust storms an optical depth of about 6.0. These values were used to consider typical dust loadings which are discussed where appropriate in the text. The $Q_{scat}$ and $Q_{ext}$ values used to calculate the relative contribution of absorbance and scattering in the UV range for a given dust optical depth were derived from Zurek, 1978 and were taken as follows ($\lambda$,$Q_{scat}$, $Q_{ext}$); 201, 1.2698, 2.1783; 308, 1.4481, 2.2182; 388, 1.9791, 2.3414; 412, 2.0376, 2.3293. Values between these wavelengths were calculated by linear interpolation. Planetary obliquity was taken as 25.2°, eccentricity as 0.0934 and perihelion at $L_s$=250°. The albedo of the martian surface in the UV range was set at 0.1 unless indicated otherwise. The scattering asymmetry factor of the dust, (g), was set at 0.736, the value calculated for 350 nm (Pollack et al., 1979, Haberle et al., 1993). Changing g from 0 to 0.736 in our model was found to increase the UV flux calculation by only 2-6%. Martian cloud cover, which may include crystal clouds possibly formed from $CO_2$ (Lee et al., 1990) is not taken into account in the calculations and nor are terrestrial clouds. Clouds can cause attenuation of UV radiation which may reduce diurnal and seasonal exposure, so in considering cloudless skies this paper addresses the worst case environment, which is useful when considering biological effects.

The total pressure on Mars is subject to variation caused by the growth and dissipation of the southern polar cap. In the case of Viking 1, the total pressure during winter solstice (perihelion) was approximately 9 mb and for Viking 2 it was 10 mb. These pressures dropped to approximately 6.75 and 7.5 mb respectively during the summer (Hess et al., 1980). For an atmospheric pressure change of 6 mb to 10 mb over a

season, the total UVB and UVC flux is reduced by 1.63% for a dust optical depth of 0.5. These increases translate into a slightly greater reduction in the biologically effective doses to DNA (2-3%), since with larger total atmospheric pressures, the incident UV radiation is skewed more towards less biologically damaging longer wavelengths as a result of proportionally more scattering at shorter wavelengths.

Diurnal variations in pressure due to $CO_2$ sublimation and condensation are also small. Pressure variations over a day generally range up to a maximum of 3% at perihelion (Hess et al., 1980). This corresponds to a change in the total UVB and C flux of approximately 0.1-0.2%.

Effects of altitude variations on martian UV flux are also small. At the summit of Mount Olympus, which rises approximately 27 km above the martian reference datum, the atmospheric pressure may be between 0.5 and 1 mbar (Zurek, 1992). The Hellas Basin is probably the lowest point on Mars, approximately 5 km below the reference datum. Average pressure here might be approximately 10 mbar (Zurek, 1992), although it is conceivable that it would rise higher than this at perihelion, since 10 mbar was found at the Viking landing site during perihelion. Nevertheless, regardless of both the pressure and altitude uncertainties, the total UVB and UVC variation between the Hellas Basin and the summit of Olympus Mons probably spans a range that lies between 2 and 3% on either side of average UV values found at the reference datum. The calculated 2% enhancement in UV flux near the summit of Olympus Mons may not reflect the actual UV radiation environment experienced on the structure. Classical observations of Olympus Mons and of other high constructs on Mars indicate that the volcano is the site of frequent cloud cover, most likely $CO_2$ cirrus (e.g., Martin et al. 1992). The frequent presence of such clouds is likely to be the prime controller of the local UV radiation regime. During the 1981-1982 opposition, Akabane et al. (1987) measured the optical thickness of an Olympus Mons cloud, attributing to it a maximum value of 0.5. To first order then, the reduction in UV flux on Olympus Mons due to

cloud cover is high enough to entirely cancel the effect of increased flux due to altitude relative to the reference datum level.

Unless otherwise stated, ozone abundances in the martian atmosphere were assumed to be negligible. The Martian polar regions experience some production of ozone during the winter and in early spring and fall when atmospheric temperatures drop (Barth et al. 1973, Barth and Dick 1974, Lindner 1991). The quantity of ozone measured by Mariner 9 was equivalent to a maximum column abundance of $1.61 \times 10^{17}$ $cm^{-2}$ in the north polar region (50° to 75°N). This quantity was measured in winter and slowly decreased until it vanished in the early summer. In the southern polar region this value was about $9.41 \times 10^{16}$ $cm^{-2}$ at maximum value in fall. These values are approximately two orders of magnitude less than typical values found on Earth (~$8 \times 10^{18}$ $cm^{-2}$ for equatorial regions). Fig. 1. shows the incident UV flux at 60°N, at noon in spring for a zenith angle of 60°. The predominant effect is a reduction in radiation around 250 nm.

For the calculation of present day UV radiation on earth, Rayleigh scattering of air molecules was calculated and ozone at a column abundance of $8.085 \times 10^{18}$ $cm^{-2}$ was assumed (i.e. 300 Dobson Units). This value is typical for mid-latitude and equatorial regions. The extraterrestrial spectrum provided by Nicolet (1989) was used in the model.

(ii) Calculations on biologically weighted weighted irradiance

The effect of UV radiation on a biological system is represented by an action spectrum ($\varepsilon[\lambda]$). This is a plot of relative biological effect (usually some measure of damage) against wavelength of irradiation. Whole organism action spectra will depend upon the combined effect of repair and protection mechanisms. In Fig 2., the action spectra for DNA inactivation and photosynthesis inhibition of isolated spinach chloroplast function (also used as a proxy for photosystem inhibition in cyanobacteria

since the photosystem II proteins are similar) are shown. Action spectra below 280 nm are not generally measured since wavelengths <280 nm are not physiologically relevant on Earth. However the absorption spectrum and action spectrum for gel formation in DNA (cross-linking) down to 180 nm is known (Setlow and Doyle 1954). DNA damage at wavelengths >280 nm (Green and Miller 1975), the action spectra for DNA lesion and spore survival in Bacillus subtilis (Lindberg and Horneck 1991) as well as inactivation of spores in earth orbit (Horneck, 1993) have also been measured. This data allows for an approximation of a general action spectrum for DNA damage across the UV range experienced on the martian surface which is shown in Fig. 2.

Since DNA is the primary target of UV radiation damage, and this damage is the greatest factor responsible for decline in organism function, many micro-organism action spectra for mortality or loss of viability are very similar to the DNA inactivation spectrum presented in this paper (e.g., that for E.coli, Jagger 1985 or for Streptomyces griseus, Keller and Horneck, 1992).

The product of the action spectrum (arbitrarily normalized to 300 nm) and the spectral irradiance distribution of the incident radiation ($E[\lambda]$) provides the biologically weighted irradiance ($\varepsilon[\lambda]E[\lambda]$). Numerical approximation of the integral of these curves provides the biologically effective irradiance ($E^*$) at a given instant in time :

$$E^* = \sum_{\lambda=200}^{400\ nm} \varepsilon[\lambda]\, E[\lambda]\, \Delta\lambda$$

The data can be integrated across the day to provide a daily weighted fluence. In Table I, the daily weighted fluence for DNA inactivation is calculated for earth and Mars. The instantaneous present-day weighted irradiances for DNA and chloroplast damage on the surface of present-day Mars at a anith angle of 0° are similar to those calculated previously (Cockell and Andrady, 1999).

## UV RADIATION ON PRESENT-DAY MARS - PLANETARY PROTECTION IMPLICATIONS

A concern of planetary exploration is the protection of extraterrestrial environments from contamination, particularly when mission goals include life detection experiments.

Recent data have been gathered on the effects of UV radiation on Bacillus subtilis spores exposed to vacuum and dehydration (Horneck 1993, Dose and Klein 1996). Bacillus subtilis spores are a good model organism for the examination of planetary protection issues since studies on the microbiological profile of the Viking landers (Puleo et al. 1977), showed that Bacillus spp. comprised between 23 and 47% of the bacterial load of the spacecraft prior to sterilization. In conditions where microbiological cleanliness is not paramount, about 95% of the load is still composed of Bacillus spp. and human borne organisms such as Micrococcus and Staphylococcus, such as the loading found on the Apollo spacecraft (Puleo et al. 1973). For extensive martian human exploration strategies, response of other, more resilient soil microbes may be important. Work that simulated martian conditions including temperature, atmospheric composition and UV radiation, showed that after two days 0.3% of aerobic soil microbes in a generic soil sample had survived (Green et al. 1971). Since species level analysis was not undertaken and since the exact spectral output from the Xe-arc lamps used to simulate the martian UV flux are not known, it is difficult to quantitatively assess this work. However, it is plausible that from a raw soil sample, some species might even survive many days exposure to the martian conditions.

UV survival data gathered on earth or in orbit can be used to assess the effects of the martian UV radiation environment on terrestrial organisms, assuming that reciprocity holds, i.e. the total dose and not the dose rate is the important parameter in defining percent loss of viability. However, assuming that the microbes are not growing

and that active repair processes are not operative, then for most terrestrial organisms transferred to Mars, reciprocity is likely to hold. It is also assumed that the spectral composition of the source is not important. This condition can a problem, since there may well be non-linear relationships between wavelengths leading to different results between, for example, lamps and UV spectral irradiance in earth orbit (e.g. Horneck 1993). Nevertheless, for planetary protection purposes, enough data does exist to provide reasonably accurate qualitative conclusions about the martian surface and rates of microbial decline.

(i) Microbial decline for two mission scenarios.

Using the radiative transfer model, the UV fluence across the solar day has been calculated for two Mars mission scenarios. The UV flux on the first day following the landing of the Pathfinder spacecraft is shown in Fig. 3.

To calculate the loss of viability of Bacillus subtilis HA101 spores, we used the data acquired from 50-300 nm by Munakata et al. (1991) under evacuation (0.01 mbar). The fluences for given levels of viability loss in their experiments were converted from photons to $W/m^2$ for their measurements at 235 nm and multiplied by their value of the inactivation rate constant at this wavelength for the B. subtilis HA 101 spores (3.95) in order to provide a biologically weighted fluence. The martian UV flux at different times of the day was weighted to their action spectrum based on the inactivation rate constants from 190 to 300 nm and integrated across the UV region to provide a biologically weighted fluence on the martian surface. The graph of biologically weighted fluence versus survival at 235 nm was then used to calculate the loss of viability under the given martian UV fluences.

Dose and Klein (1996) also measured loss of B. subtilis TKJ 3412 viability under UV radiation. They measured an $F_{37}$ value (37% of viability left) of $50J/m^2$ for spores in

vacuum ($3 \times 10^{-6}$ mbar) at 298K exposed to radiation from a mercury vapor lamp emitting primarily at 254 nm. Spectrally weighting their data against the DNA action spectrum provides a biologically effective irradiance of 1270 $J/m^2$ for $F_{37}$. Spectrally weighting the martian UV flux against the action spectrum and calculating loss of viability for a given fluence gives the same data as that acquired from Munakata et al. with a 10% error. Dose and Klein apparently have a sub-population that survives large fluences (>1000 $J/m^2$), so that at high fluences, a small proportion of organisms survive and divergence with the data of Munakata et al. occurs. In the case of Pathfinder, their data predicts that after 2.5 hours on the martian surface 1% still remain.

Sterilization could only occur two hours after landing since the Pathfinder landed prior to sunrise at 3:11 local solar time. However, once the Sun begins to rise, loss of biological viability is quite rapid. Within thirty minutes less than 3% of the spores remain viable. Loss of most of the viability occurs early in the day. At this time of the day diffuse flux is almost equal to the exposed flux (the sum of direct and diffuse radiation). This implies that during the morning shaded areas of the spacecraft would have been sterilized at the same rate as exposed surfaces.

Data are also shown for NASA's Mars polar lander in Fig. 4, using the projected Mars Global Surveyor 1999 lander data. It assumes landing on 3rd December 1999 at 77°S. In (a.), data are shown for average dust loading ($\tau$=0.5). for (b.), UV flux during a mild dust storm is also shown ($\tau$=2.0). During the spring when temperatures rise and insolation increases, the polar ozone layer has a column abundance of $2.68 \times 10^{16}$ $cm^{-2}$ (Barth et al. 1973) . This column abundance was incorporated into the calculation. It was also assumed that the contribution of the polar hoods to UV absorption during the landing phase is not significant since landing occurs during southern summer when the polar hoods are not expected to be present. Because of the proximity to ice and solid $CO_2$, the albedo of the surface was taken as 0.4 rather than 0.1 in these calculations, although the effect of the albedo change on the calculated UV flux is small (<2%).

For the polar region, the higher solar zenith angle at midday means that the instantaneous flux is approximately 50% of that encountered at the Pathfinder site (19.44°N), but the total daily fluence is about 76% of the Pathfinder site because of the 24 hour light cycle. From a planetary protection viewpoint, the 24 hour polar light cycle provides the opportunity for 24 hour sterilization, but throughout most of the day, particularly around midnight, the higher solar zenith angle increases the time required for mortality. However, loss of viability is still quite rapid. Even with a dust storm ($\tau$=2.0), the diffuse UV radiation near midnight is capable of reducing viability down to 10% within 30 minutes.

Survival may be possible for some of these organisms if they are picked up in dust storms and redeposited under layers of dust. Pollack et al. (1979) estimate that the mass loading of dust on a surface is approximated by $5 \times 10^{-4}\tau$, where $\tau$ is the optical depth. Thus for a relatively clear day with $\tau$=0.5, and taking the density of martian dust as $3 g/cm^3$, the thickness of the dust on a surface, if that dust where to settle, would be 0.8$\mu$m and for a dust storm of $\tau$=6.0, the thickness would be 10$\mu$m. Using a thin layer (~100 $\mu$m) of JSC-1 Mars simulant (palagonite) placed onto a quartz cover slip and measured for transmittance, it was found that UV reductions will at least an order of magnitude. After a passive covering of dust following a dust storm some microbes will have the ability to survive the martian environment for many days. If the depth of the dust is increased by active turnover of surface material, such as during a dust devil, then some microbes may survive indefinitely until they are re-exposed to UV radiation.

The 1992 NRC Task group on Planetary Protection recommendations (NRC, 1992) concluded that, "during the entire martian year, the UV flux is sufficient to sterilize the martian surface". As shown here, the martian UV radiation environment can be considered sterilizing for the majority of human derived microbes introduced on the surface of spacecraft. However, even a thin dust layer will negate this conclusion.

## CONCLUSIONS

The martian UV radiation environment has high UVB and UVC fluxes. The biologically effective irradiances of DNA inactivation can be estimated. They are three orders of magnitude higher than typical values found on earth at the corresponding zenith angle (Table 1.). For planetary protection, the assumption that the martian surface UV flux is 'sterilizing' is probably correct for unadapted earth-derived organisms exposed to the extreme environmental synergisms of the martian surface. However, even a small layer of dust is likely to considerably increase survivability.

For the surfaces of spacecraft exposed to the martian UV flux, sterilization will occur quite rapidly. As shown in this report, even shaded surfaces will be sterilized by the diffuse UV flux quite quickly. For the polar lander sterilization can occur over 24 hours because of the 24 hour sunlight. Spacecraft at lower latitudes can only be sterilized during the day. Thus, microbes on the surface of the spacecraft are unlikely to represent a contamination to life detection experiments although clearly the organic remains of dead microbes might affect organic detection experiments.

The salient conclusion from these calculations is that viable microbes on exposed and even shaded surfaces exposed to UV radiation will be killed. However, microbes removed from the spacecraft and covered in a thin dust layer will be able to survive in this refuge from the UV flux. Such microbes could represent a contamination problem for life detection experiments or organic detection experiments, particularly in samples to be returned to earth or scooped and analyzed in the spacecraft.

The likelihood of microbes being removed and covered in dust will be increased during martian dust storms and on spacecraft that land during the night, giving time for microbes to be removed by wind and redeposited under a thin dust layer. This might have been the case, for example, with the Pathfinder spacecraft which landed two hours before sunrise. In general day-time landings will increase the efficacy of UV sterilization

of spacecraft and reduce the likelihood of microbes being removed and redeposited under dust before they are killed.

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TABLE I. UV fluences at the equator (for vernal equinox) of Mars and earth. Daily integrated data are provided and for a solar zenith angle of 0°. Values at zenith angle = 0° are given in $W/m^2$, values of daily fluence and doses are given in $kJ/m^2$.

| | UVC and B (200-315 nm) | UVA (315-400 nm) | DNA Effective Irradiance |
|---|---|---|---|
| Mars | | | |
| Daily fluence | 361 | 1126 | 3183 |
| Zenith angle 0° | 13.2 | 41.5 | 116.4 |
| Earth | | | |
| Daily fluence | 39 | 1320 | 2.10 |
| Zenith angle 0° | 1.86 | 52.81 | 0.10 |

Fig. 1. Irradiance curves. Data shows extraterrestrial spectrum and corresponding fluxes at the martian surface. Two cases are provided. First, flux received at a zenith angle of 0° (equator at vernal equinox) with no ozone. Second, flux for a solar zenith angle of 60° (solar zenith angle at noon) at 60°N during spring (vernal equinox) with an ozone column abundance of 8.1 X $10^{16}$ $cm^{-2}$. For both cases data is provided for a clear day with some dust loading ($\tau$=0.5) and a medium-scale dust storm ($\tau$=2.0). Here UVB radiation is defined as 280-315 nm according to the conventions adopted by the International Commission on Illumination (CIE).

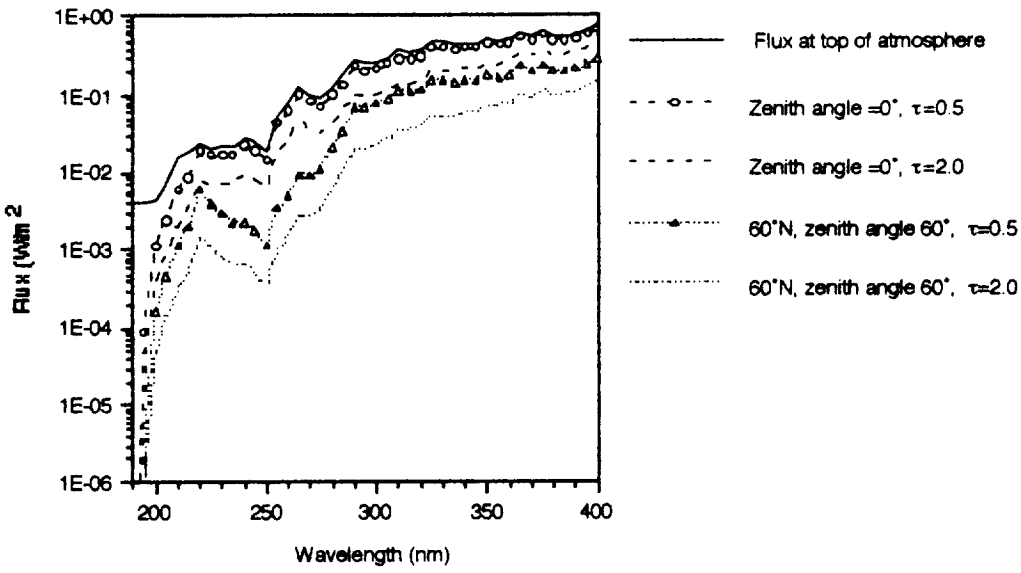

Fig 2. Typical action spectra for
various types of biological damage

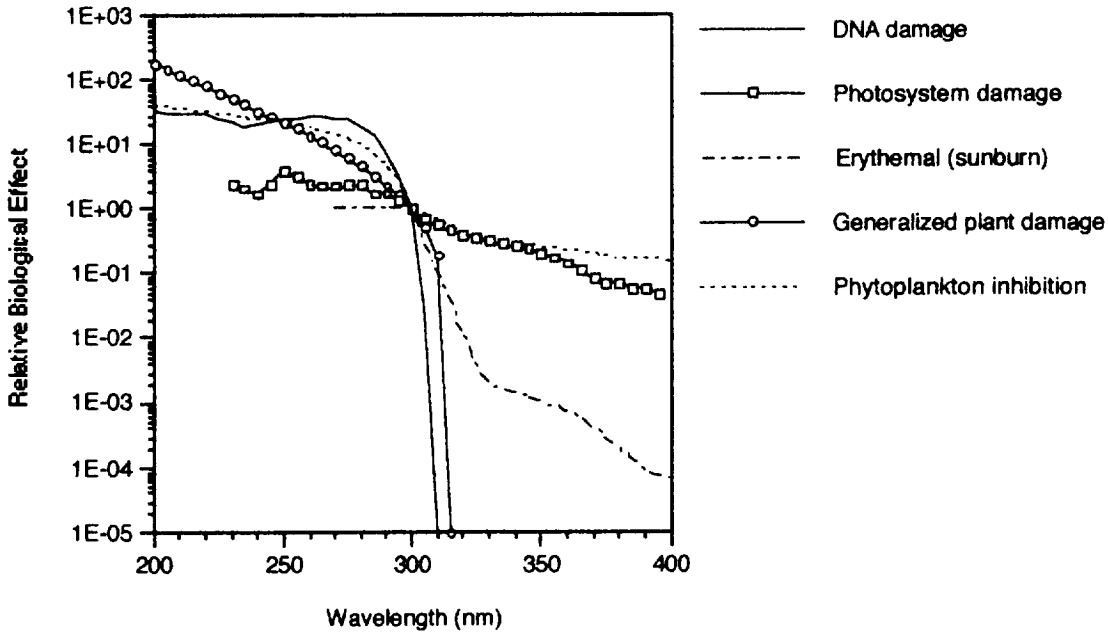

Fig. 3. UV flux on the day of the Pathfinder landing (4 July 1997). Data also shows decline in Bacillus subtilis viability associated with the UV flux. Flux is shown for an exposed surface (direct plus diffuse UV) and for a shaded surface (diffuse only) ($\tau$=0.5).

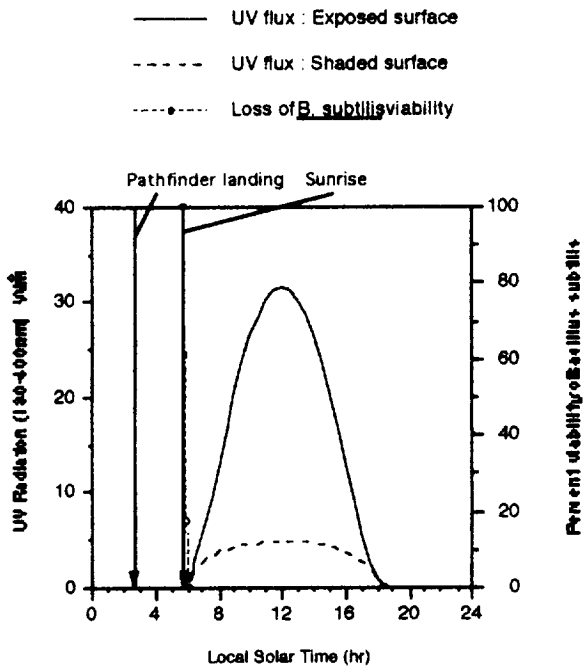

Fig. 4. UV flux at 77°S for a polar lander. Data presented is for a landing on 3 December 1999. Data is presented for a clear day with some dust loading ($\tau$=0.5) and for a medium-scale dust storm at the landing site ($\tau$=2.0). Total daily fluence is about 76% of the UV fluence at the Pathfinder site. Flux is shown for an exposed surface (direct plus diffuse UV) and for a shaded surface (diffuse only).