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The Ultraviolet Environment of Mars: Biological Implications Past, Present, and Future

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A radiative transfer model is used to quantitatively investigate aspects of the martian ultraviolet radiation environment, past and present. Biological action spectra for DNA inactivation and chloroplast (photosystem) inhibition are used to estimate biologically effective irradiances for the martian surface under cloudless skies. Over time Mars has probably experienced an increasingly inhospitable photobiological environment, with present instantaneous DNA weighted irradiances 3.5-fold higher than they may have been on early Mars. This is in contrast to the surface of Earth, which experienced an ozone amelioration of the photobiological environment during the Proterozoic and now has DNA weighted irradiances almost three orders of magnitude lower than early Earth. Although the present-day martian UV flux is similar to that of early Earth and thus may not be a critical 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. Microbial strategies for protection against UV radiation are considered in the light of martian photobiological calculations, past and present. Data are also presented for the effects of hypothetical planetary atmospheric manipulations on the martian UV radiation environment with estimates of the biological consequences of such manipulations.

Key Words: **atmospheres; evolution; exobiology; Mars; photochemistry; radiative transfer.**

1. INTRODUCTION

On Mars the lack of a significant ozone layer and the lower total atmospheric pressure than that of Earth results in an environment with a higher surface flux of ultraviolet radiation. This UV flux has been considered to be a significant evolutionary selection pressure 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, probably including cyanobacteria, had colonized Earth (Schopf and Packer 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 the evolution of life (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 the lack of preservation of organics (Oro and Holzer 1979, Stoker and Bullock 1997). Although the martian UV flux may not be critically limiting in the evolutionary context, biologically effective

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irradiances will of course be significant for an unadapted present-day terrestrial biota transferred to Mars, and particularly for artificial ecosystems (Cockell and Andrady 1999). DNA weighted irradiances are approximately three orders of magnitude higher than typical clear sky values on Earth at comparable zenith angles.

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 paper, a theoretical assessment of the past and present UV radiation environment on Mars is presented and the biological and evolutionary consequences are discussed. Implications for the introduction of terrestrial organisms to the martian surface, relevant to planetary protection concerns and long-term human exploration are considered. Effects of the alteration of the martian atmospheric composition on UV flux are addressed.

2. CALCULATION OF THE MARTIAN AND TERRESTRIAL UV RADIATION ENVIRONMENT, PAST AND PRESENT

i. Calculation of Present Martian UV Flux

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 6-mb atmosphere of CO_2 with no other significant gaseous constituents. During perihelion when the southern polar cap sublimes, the total atmospheric pressure may increase to between 9 and 10 mb as was observed during winter solstice at the two Viking landing sites (Hess *et al.* 1980). Thus, the assumption of a 6-mb atmosphere is a typical summer value for most sites on Mars. Neither H_2O (0.03%) nor the low levels of atmospheric O_2 (0.13%) have significant absorbance in the UV region at martian column abundances based on their absorption cross-sections (Yung and DeMore 1999). 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 Beer's 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 that assumes reflection on a Lambertian surface (e.g., Haberle *et al.* 1993) and is based on the two-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 and 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 that 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 (λ, 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 prudent when considering biological effects.

The total pressure on Mars is subject to variation caused by the growth and dissipation of the polar caps. 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 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 in pressure 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 toward less biologically damaging longer wavelengths as a result of proportionally more scattering at shorter wavelengths.

Diurnal variations in pressure principally caused by thermal tides 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 21.2 km above the topographic geoid (Smith *et al.* 1999), the atmospheric pressure may be between 0.5 and 1 mbar (Zurek 1992). The Hellas Basin is probably the lowest point on Mars, approximately 7.8 km below the topographic geoid. Average

pressure here is approximately 12 mbar (Zurek 1992). 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 1.61×10^{17} cm^{-2} in the north circum-polar region (50° to 75°N). This quantity was measured in winter and slowly decreased until it vanished in the summer. In the southern polar region this value was about 9.41×10^{16} cm^{-2} at maximum value in fall. These values are approximately two orders of magnitude less than typical values found on Earth ($\sim 8 \times 10^{18}$ cm^{-2} for equatorial regions). Figure 1 shows the incident UV flux at 60°N, at noon in early spring for a zenith angle of 60°. The predominant effect of the ozone is a reduction in radiation around 250 nm, consistent with previous calculations (Kuhn and Atreya 1979).

For the calculation of present-day UV radiation on Earth, Rayleigh scattering of air molecules was calculated and ozone at a column abundance of 8.085×10^{18} cm^{-2} was assumed (i.e., 300 Dobson units). This value is typical for mid-latitude and equatorial regions. The ozone cross section was taken from Daumont *et al.* (1992). The extraterrestrial spectrum provided by Nicolet (1989) was used in the model.

ii. UV Radiation on Early Earth and Mars

The composition of the atmosphere on early Earth and Mars is controversial, particularly with regard to the source of the greenhouse effect required to keep early Earth and Mars warm. Iron precipitation patterns in Precambrian paleosols on early Earth 2.8–2.2 Ga (Rye *et al.* 1995) suggest that pCO_2 may have been less than 40 mb. Also iron silicate–iron carbonate equilibria applied to the deposition of sediments in Archean banded iron formations indicate that pCO_2 was less than 0.15 bar (Mel'nik 1982). However, during the early Archean 3.5 Ga, CO_2 partial pressures may have been ~1 bar (Kasting 1993), and this may have been required if there had been no other source of greenhouse warming. Here this value is used for early Earth 3.5 Ga. It is assumed that specific UV absorbers such as sulfur (e.g., Kasting *et al.* 1989) or an organic haze (Sagan and Chyba 1997) were not present. It is plausible that a greenhouse gas such as CH_4 either in the early terrestrial or martian atmospheres could have been photolyzed to produce a hydrocarbon smog (Sagan and Chyba 1997) which would have provided UV protection for organisms on the surface of either planet. In this case, the results presented in this paper are an

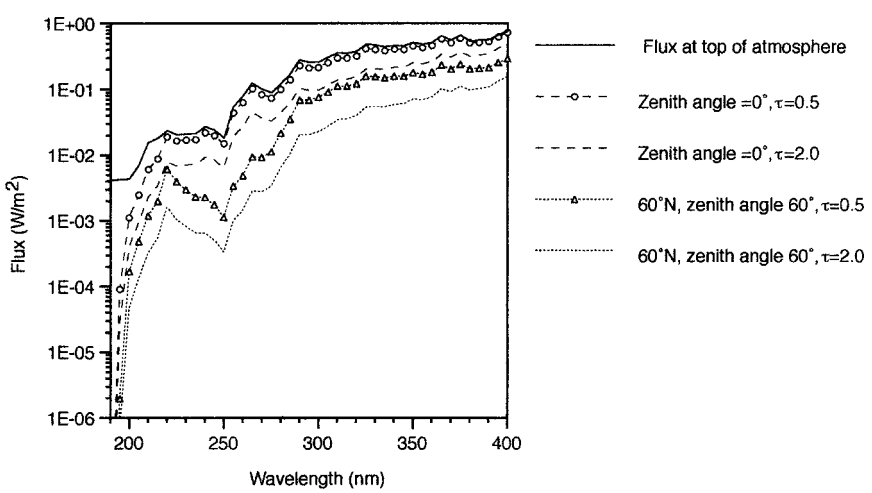

FIG. 1. Irradiance curves. Data show extraterrestrial spectrum and corresponding fluxes at the present-day martian surface. Two cases are provided. First, flux received at a zenith angle of 0° (equator at vernal equinox) with no ozone. Second, flux for a solar zenith angle of 60° (solar zenith angle at noon) at 60°N during spring (vernal equinox) with an ozone column abundance of 8.1×10^{16} cm^{-2}. For both cases data are provided for a clear day with some dust loading ($\tau = 0.5$) and a medium-scale dust storm ($\tau = 2.0$).

upper limit on UV exposure on the early planets. Indeed, in the case of Mars it would mean that our conclusions for Mars concerning the increasing importance of UV radiation as a detrimental biological stressor over time are an underestimate.

For early Mars an atmosphere composed of 1 bar CO_2 is taken, which might be the upper value for the atmospheric reservoir at the end of late bombardment (Haberle *et al.* 1994). Forget and Pierrehumbert (1997) calculate that for CO_2 pressures above this, CO_2 condensation clouds in the martian atmosphere would be sufficient to warm the surface and allow liquid water. Since some geomorphic features on Mars can be explained by subfreezing periglacial processes, CO_2 partial pressures could have been as low as 0.3 bar (Forget and Pierrehumbert 1997). In the case of Mars the N_2 content of the early atmosphere was taken as 0.1 bar (approximately 10% of atmospheric composition) and for early Earth N_2 was taken as 0.8 bar (the same as the present-day value). N_2 assumptions are not so critical since N_2 is not a UV absorber, although high partial pressures of N_2 do increase Rayleigh scattering. Although H_2O can absorb UV radiation to produce H_2O_2, which is a UV absorber up to 350 nm, H_2O, which is generally located at lower altitudes corresponding to the troposphere, is shielded by higher altitude CO_2 (Yung and DeMore 1999) that has a similar cross section. Thus the H_2O contribution to UV absorbance in the early atmospheres is assumed to be negligible. In the case of both early Earth and Mars a dust optical depth of 0.1 was taken, which assumes a worst-case photobiological exposure, the most relevant calculation for considering biological effects.

A 25% less luminous Sun is assumed for early Earth and Mars based on the increase of luminosity associated with the projected evolution of a G2 main sequence star (Newman and Rood 1977, Gough 1981). This change of luminosity may have been equivalent to ~35% less UV radiation between 200 and 300 nm (Zahnle and Walker 1982), which is assumed in these calculations. The possibility that the early Sun emitted a proportionally higher UV flux than visible wavelengths as a result

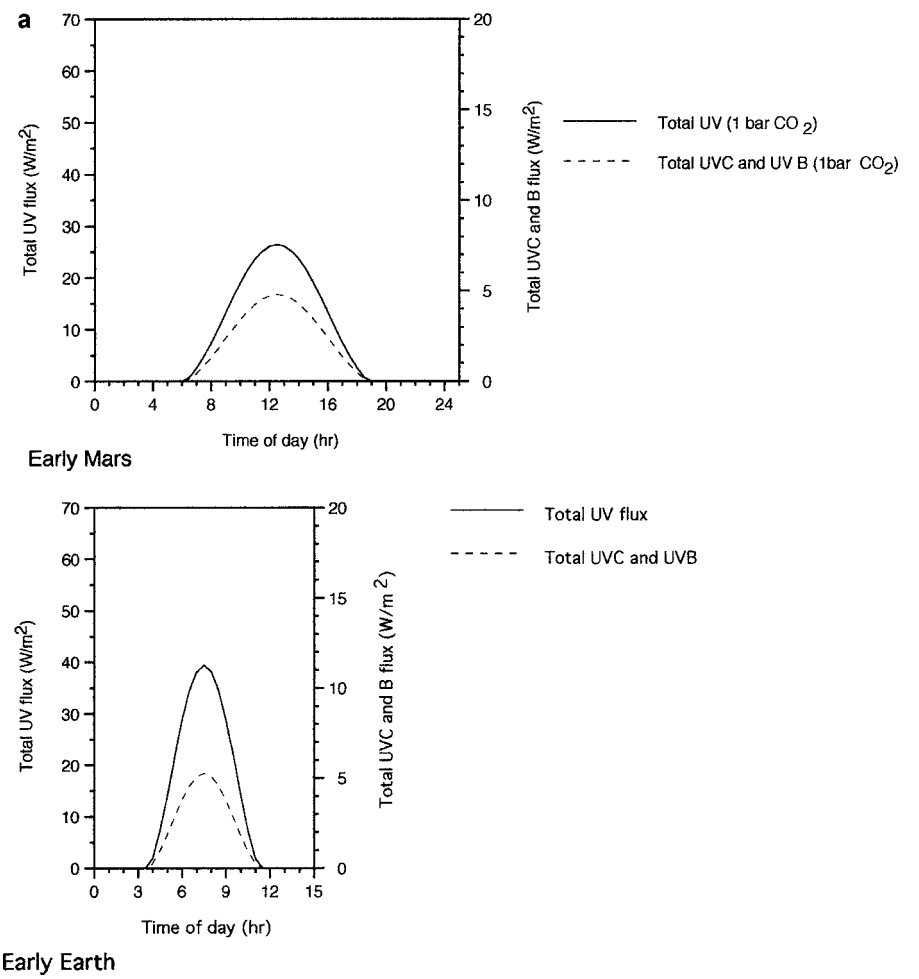

FIG. 2. (a) UV flux at the surface of early Earth and Mars (3.5 Ga) for the equator at vernal equinox (or an early equivalent on Mars). (b) UV flux on present-day Earth and Mars for the equator at vernal equinox. In both cases total UV fluence is shown along with the total of UVC and UVB (the biologically most important wavelengths). In all cases optical depth of dust is taken as 0.1. Here UVB radiation is defined as 280–315 nm according to the conventions adopted by the International Commission on Illumination (CIE).

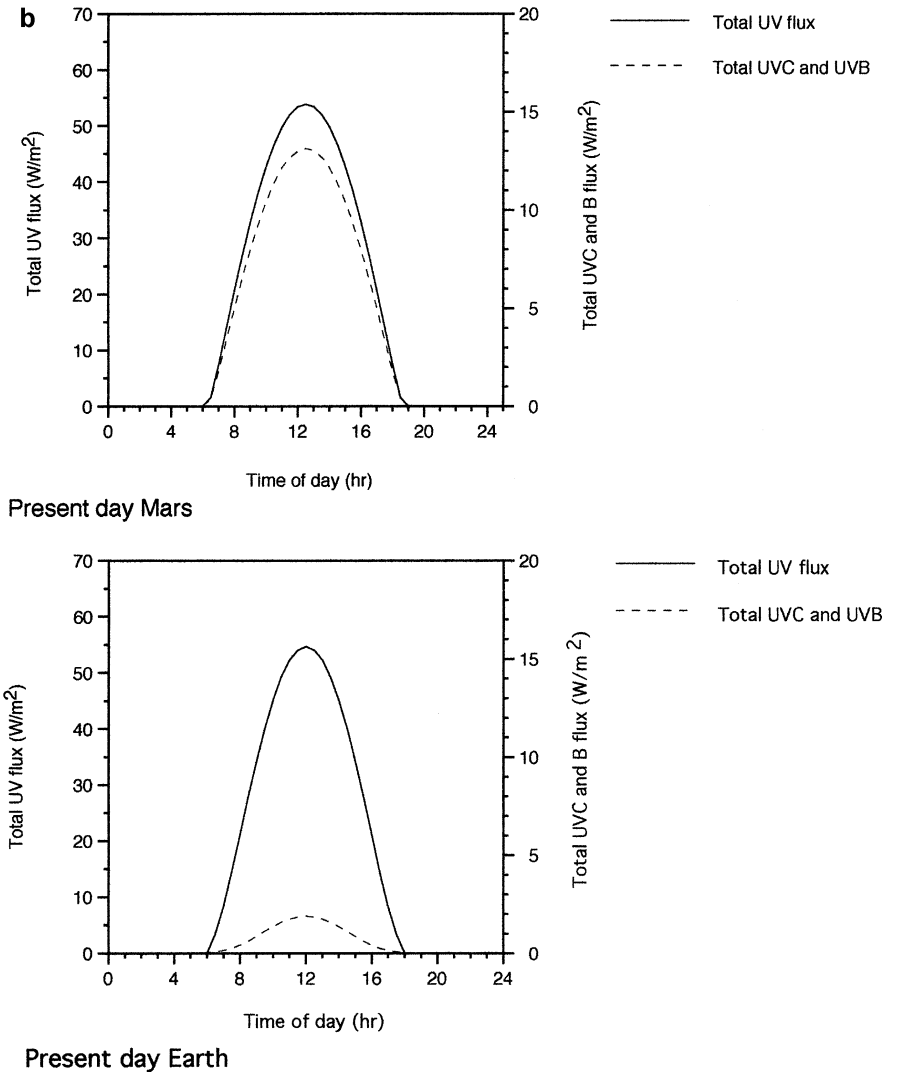

FIG. 2—*Continued*

of its early T-Tauri stage is not considered to be important since these wavelengths are generally confined to the region <200 nm (Zahnle and Walker 1982, Canuto *et al.* 1982) and do not reach the surface of the planet because of CO_2 absorption.

Present-day obliquities for both planets were taken. The obliquity of Earth is Moon stabilized (Ward 1992, Touma and Wisdom 1994, Laskar *et al.* 1993) and oscillates $\pm 1.3^\circ$ around the mean of 23.3° (Laskar *et al.* 1993). During the Archean obliquity variations may therefore have been less extreme than is proposed for Mars. The martian obliquity probably oscillates more chaotically (Ward 1992) and recent values suggest between $\sim 0^\circ$ to 60° (Laskar and Robutel 1993). Some discussion of effects of obliquity on UV exposure on Mars is provided in Section 3.

Day length has changed since the Archean. In the case of Earth, rotational drag has been mainly caused by tidal forces exerted by the Moon as well as tidal forces from the Sun–Earth interaction (Johnson and Nudds 1974). Three to 3.5 Ga the day length may have been 15 h, lengthening to 20 h at the close of the Precambrian 570 million years ago (Walker *et al.* 1982). For our calculations a 15-h day is assumed. For Mars, lunar tidal drag has not existed. Lunar drag contributes about 78% of the tidal force that results in the slowing down of Earth's rotation (Johnson and Nudds 1974). Among other parameters tidal dissipation is proportional to the mass and radius of the planet and is inversely proportional to the semimajor axis. Thus, we would expect tidal dissipation on Mars particularly, without oceans, to be much less effective than on early Earth and probably the present day length is similar to the primordial day length. For both past and present-day Earth and Mars, UV data over the day are shown in Figs. 2a and 2b. Note that the model predicts that total UV flux is approximately the same on present-day Earth as early Earth under cloudless skies. This is because UVA is not attenuated by ozone and so was about 35% less on early Earth than present-day Earth due to the faint young Sun. However, the UVB and C flux

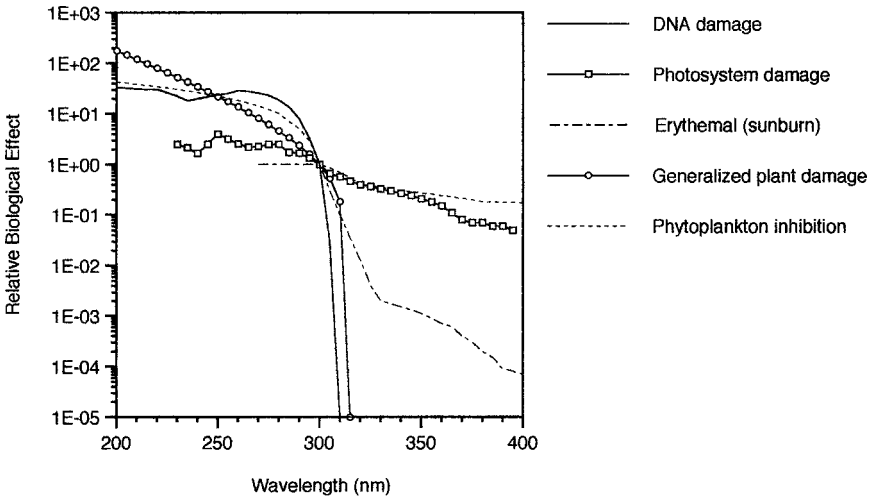

FIG. 3. Action spectra used to assess martian biologically effective irradiances. All spectra are normalized to 300 nm.

was greater on the surface of early Earth. When measured as a total, the UV flux is similar although the wavelength distribution has changed.

iii. Calculations on Biologically 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 radiation. Whole organism action spectra will depend upon the combined effect of repair and protection mechanisms. In Fig. 3, 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 action spectrum for inactivation of *Bacillus subtilis* spores in Earth orbit has been measured (Horneck 1993) as well as gel formation in DNA (cross-linking) down to 180 nm (Setlow and Doyle 1954). DNA damage at wavelengths $>$280 nm (Green and Miller 1975) and the action spectra for DNA lesion and spore survival in *Bacillus subtilis* (Lindberg and Horneck 1991) has been measured. These data allow 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. 3.

Since DNA is the primary target of UV radiation damage, and this damage is the greatest factor responsible for decline in organism function, many microorganism action spectra for 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)).

In the case of chloroplasts the studies were only undertaken down to 230 nm (Jones and Kok 1966). Here we show the values down to 230 nm (Fig. 3). On Earth, UVA (315–400 nm) primarily exerts its affects through indirect oxidative damage resulting from reactive O_2 species, rather than by direct photochemical damage (Jagger 1985). However, although the atmosphere of Mars is essentially anoxic we assume here that photosynthetic organisms would be producing O_2 in their chloroplast microenvironment, so the UVA contribution is included.

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:

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

The data can be integrated across the day to provide a daily weighted fluence. In Table I, the daily weighted fluence for DNA inactivation and photosystem damage is calculated for Earth and Mars based on the UV radiation data presented in Fig. 2. The instantaneous present-day weighted irradiances for DNA and chloroplast damage on the surface of present-day Mars at a zenith angle of 0° are similar to those calculated previously (Cockell and Andrady 1999).

3. UV ON EARLY MARS—BIOLOGICAL IMPLICATIONS

The modeled instantaneous DNA biologically effective irradiance on early Earth for a solar zenith angle of 0° (noon) was 21% greater than that for early Mars (Table I) for cloudless skies. These data agree with conclusions made earlier that UV flux on early Mars was probably not a critical constraint to the evolution of life (Mancinelli and Banin 1995, Cockell 1998). It should be noted that there are some uncertainties. If, for example, Earth had possessed a CH_4-generated hydrocarbon smog and not Mars, then the lack of such an atmospheric shield on Mars could have negated the effect of Sun–Mars distance

TABLE I
UV Fluxes, Fluences, and Biologically Weighted Irradiances at the Equator (for Vernal Equinox) of Mars and Earth, 3.5 Gyr Ago and Present Day

	UVC and B (200–315 nm)	UVA (315–400 nm)	DNA effective irradiance	Photosystem effective irradiance
Early Mars (1 bar CO_2)				
Daily fluence	119	542	838	231
Zenith angle 0°	4.8	22.3	33.8	9.5
Early Earth				
Daily fluence	78	519	615	193
Zenith angle 0°	5.2	34.1	41.0	12.7
Present day Mars				
Daily fluence	361	1126	3183	689
Zenith angle 0°	13.2	41.5	116.4	24.5
Present day Earth				
Daily fluence	39	1320	2.10	0.52
Zenith angle 0°	1.86	52.81	0.10	9.71

Note. Daily integrated data are provided (assuming current obliquities) and for a solar zenith angle of 0°. See text for description of atmospheric models. Values at zenith angle = 0° are given in W/m^2; values of daily fluence and doses are given in kJ/m^2.

and the planets might have had comparable instantaneous UV regimes at zenith angle 0°. Furthermore, integrated over time, the photobiological conditions on the early planets could have been strongly influenced by which planet was more cloudy and the optical depth of these clouds in the UV region. Thus, the calculations presented here would apply to the instantaneous dose that an organism would have to be capable of tolerating on a clear day at zenith angle 0°. How common this was for either planet cannot be determined without knowledge of the cloudiness of the early planets.

The data show that sidereal period is important when assessing total biologically effective fluence. On early Earth biologically effective DNA irradiance is 21% greater than that on early Mars for a zenith angle of 0°, but the daily fluence is actually less assuming similar atmospheric CO_2 inventories. This is because of the shorter Archean day length. The importance of day length relates to an organism's ability to repair DNA damage. If the protection mechanisms and rates of repair are sufficient to keep up with DNA damage as is observed in some terrestrial organisms (Lesser *et al.* 1994), then accumulated damage is not a concern. On early Mars, putative organisms on the surface might have needed a lower tolerance to instantaneous damage compared to organisms on the surface of early Earth, but the day length, which was twice as long as on Earth, would have increased their daily accumulated damage.

The instantaneous DNA weighted irradiance for early Earth is calculated as 41 W/m^2. This is lower than the 127.1 W/m^2 estimated earlier (Cockell 1998), probably because a radiative transfer model was not used in the previous estimation, but rather a 25% attenuation was assumed across the UV region. Also here a pCO_2 of 1 bar is taken. At 3 Ga, pCO_2 may have been nearer to 40 mb (Rye *et al.* 1996) and under such conditions the DNA weighted irradiance would be ~96 W/m^2, closer to the previous estimate. Thus, for present-day Mars the instantaneous maximum dose is greater than on early earth (181%) with pCO_2 of 1 bar, but similar to the value at 3 Ga under a 40-mb CO_2 atmosphere. These values agree with previous suggestions that in the evolutionary context even the present-day instantaneous martian UV flux would not in itself prevent life (Cockell 1998). However, the day length on present-day Mars may be about 100% greater than that on early Earth. This would increase accumulated daily damage compared to early Earth. If exposed organisms in the terrestrial Archean possessed repair processes that could keep up with damage throughout the day, then it is probable that accumulation of damage during the present martian day might still be within the threshold of efficient repair processes. Similar conclusions can be drawn regarding photosystem damage (Table I).

The chaotic behavior of martian obliquity (Laskar and Robutel 1993) and the less extreme changes in terrestrial obliquity are also a factor for UV exposure. At low obliquities, most of the surface of the planets is subjected to a light/dark cycle, so that the total daily UV flux calculated for the equatorial region at vernal equinox can be considered an upper limit for UV exposure for most organisms. At high obliquities greater proportions of the planets are subjected to long periods of darkness. During such phases on Mars habitats for exposed nonphotosynthetic life that are protected for ~320 days in darkness may have existed, but during the rest of the year organisms would be exposed to long periods of continuous UV exposure. From a biological standpoint this is analogous to many polar microbial communities found on Earth that need to repair 24 h of continuous UV damage (e.g., Vincent and Quesada 1994). Because at higher latitudes the midday zenith angle is higher, then total daily fluence may not be much worse than at the equator at vernal equinox, the damage is just spread over the whole day.

In the more recent history of Mars obliquity alterations have probably caused changes in pCO_2 caused by freeze out of the

atmosphere (Lindner and Jakosky 1985). However, even at an obliquity of 9° when pCO_2 may have been as low as 0.1 mbar, increases in DNA-weighted irradiances at a zenith angle of 0° amount to less than 10%. Thus, the most important photobiological consequence of martian obliquity alterations is the change in temporal exposure of UV radiation, not the change in absolute UV flux.

Many physical and biological strategies that have been proposed to have existed on early Earth to mitigate UV damage have been suggested to be sufficient to reduce biologically effective irradiances on Mars (Cockell 1998). Here, some specific exposed habitats that have previously been suggested to be of importance to martian exobiology (e.g., Sagan and Pollack 1974, Rothschild 1990, Clark 1998, Cockell 1998, Wynn-Williams and Edwards 2000) are briefly discussed. They are martian dust, evaporitic deposits, endolithic habitats, and ice covers.

Iron compounds can provide a UV screen for life (Olsen and Pierson 1986, Pierson *et al.* 1993, Kumar *et al.* 1996) and martian regolithic dust has specifically been proposed as a suitable refuge for life (Sagan and Pollack 1974). On Mars iron is the second most abundant element in surface materials after silicon and is present at about 10.5 wt% by elemental composition (Rieder *et al.* 1997); however, much of this iron may be bound up as insoluble iron oxides such as hematite or maghemite. Terrestrial palagonite (JSC Mars-1 simulant) is a useful analog of martian soil, possessing the same elemental composition and reflectance properties (Allen *et al.* 1998). One and a half grams of JSC Mars-1 soil simulant was left in 5 mL of water overnight. The sample was spun and the absorbance of the supernatant was read. Figure 4 shows the absorbance spectra of this material compared to 1 mM $FeCl_3$ (Fe^{3+}) and 20 mM $FeSO_4$ (Fe^{2+}) (Sigma Chemicals, St Louis, MO) measured at 1-nm intervals in a Perkin-Elmer lambda 2 spectrophotometer (Perkin-Elmer, Wellesley, MA) using distilled water as a standard. For the palagonite at the point between UVC and UVB (280 nm), transmittance would be less than 40% beneath a 1-cm water column, although most of this attenuation is due to scattering from small insoluble particles, rather than direct absorbance. Thus, although direct iron absorption may have been limited it is possible that martian dust deposited in lakes could still provide a UV screen in putative ancient martian paleolakes (Doran *et al.* 1998 and references therein).

Terrestrial endolithic communities that live in the subsurface layers of rock that provide a nanoclimate against extreme external conditions (Friedmann 1982) have been proposed as possible analogs to life on Mars (McKay 1993, Wynn-Williams and Edwards 2000). They experience light levels reduced to 10% of incident at the upper layers of the colonies. At the lower levels of the colonies light levels may be reduced to 0.005% of incident levels (Nienow *et al.* 1988, Nienow and Friedmann 1993). At a depth of just 1 to 2 mm, DNA effective irradiances would be reduced to levels experienced on the exposed surface of present-day Earth ($\sim$0.1 W/m^2) under the protection of an ozone shield although light levels would still be sufficient for photosynthesis and growth. Significantly, the biomolecules left by such communities, as well as other analog cyanobacterial communities, might have sufficient recalcitrance to be used as exobiological biomarkers (Wynn-Williams *et al.* 1999, Wynn-Williams and Edwards 2000).

Salt deposits may also exist on Mars (e.g., Clark and Van Hart 1981). Theoretical (Catling 1999) and experimental (Moore and Bullock 1999) evidence for evaporitic deposits has been suggested, which is consistent with evaporitic deposits proposed for some crater basins on Mars with intracrater terraces (Forsythe and Zimbelman 1995). Such martian evaporites could provide UV protection for organisms (Rothschild 1990, Mancinelli *et al.*

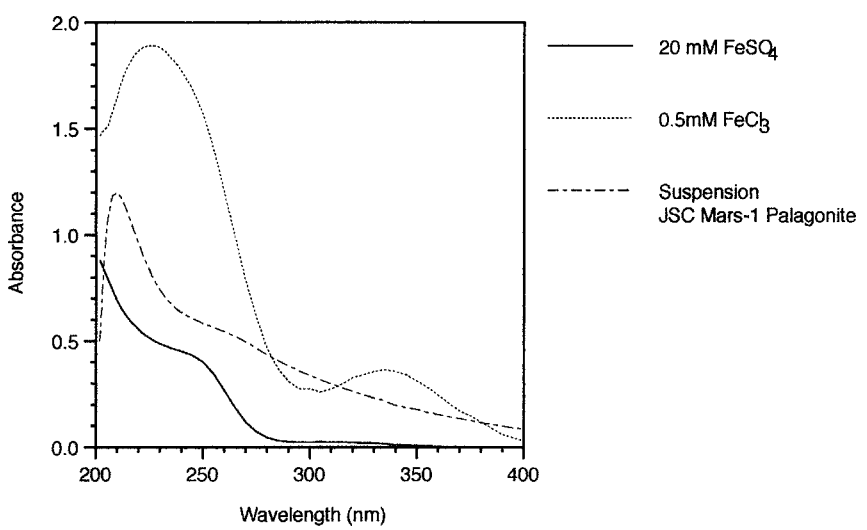

FIG. 4. Absorbance properties of Fe^{2+} and Fe^{3+} solutions. Also shown is the absorbance of the supernatant from 1.5 g of JSC Mars-1 soil simulant (palagonite) left in 5 mL of water overnight.

1998). Given the UV absorption of solid NaCl it is probable that in analogy to the endolithic habitat, just a few millimeters of salt would be sufficient to reduce DNA weighted irradiances down to values found in exposed habitats on present-day Earth.

Frozen impact lakes may have persisted on the surface of Mars (Newsom *et al.* 1996), particularly associated with impact basins (Cabrol *et al.* 1999). Organisms adapted to life beneath ice covers, of even moderate thickness, would have the advantage of this physical screening mechanism, particularly where impurities are present. Recent measurements of radiation in the 280- to 340-nm range, made beneath the perennial ice cover of an antarctic lake, indicate that UV at wavelengths less than 310 nm is hardly encountered (Kepner *et al.* 2000). This lower wavelength UVB appears to penetrate the ice to depths of no more than 1.5 m during relatively cloud-free austral summer days, when surface UV doses are quite high. The absorption coefficient is some two orders of magnitude greater at 200 nm than 450 nm (Warren 1984, Perovich and Govoni 1991), but because the UV region of the spectrum is comprised of fewer photons than the PAR (Photosynthetically Active Radiation) region, enough PAR may get through for photosynthesis. Estimated biologically effective UV irradiances immediately beneath the ice were three to five orders of magnitude less than those under full sky conditions, while incident PAR immediately under the ice is attenuated to an average of roughly 2% of surface values, similar to previously reported values (McKay *et al.* 1994). In some cases UVB may still be sufficient to inhibit microbial growth (Vincent *et al.* 1998). In extraterrestrial environments, this reduction may at least be a substantial improvement on full sky UV exposure. Additionally, water or carbon dioxide snow and frost deposited on lakes, particularly if it contained impurities from the martian surface may help absorb, reflect and scatter UV radiation, to the benefit of organisms beneath.

4. UV RADIATION ON AN ENVIRONMENTALLY DETERIORATING MARS

The UV radiation flux environment of present-day Mars under cloudless conditions is more detrimental to biology than that of the early Mars environment owing to the steady increase in solar luminosity since Zero Age Main Sequence and the reduced atmospheric attenuation caused by reduced pCO_2 (see Fig. 7 for the effects on pCO_2 on biologically effective irradiances.). However, it was discussed earlier that the present-day noon flux is probably still no worse than that of early Earth and even though daily fluence is greater, it may still be within the threshold of efficient repair processes. However, today the surface of Mars is lifeless. Why?

In many terrestrial microorganisms the detrimental effects of UV radiation may be synergistically increased by extremes such as desiccation and reduced atmospheric pressure (Lindberg and Horneck 1991, Dose *et al.* 1991, Horneck 1993, Dose and Klein 1996). On the surface of Mars the existence of oxidants in the upper layers of the martian regolith (e.g., Hunten 1979) would also be a significant additional stress to a putative surface biota.

During the history of Mars from approximately 3.8 to 2 Ga, temperatures dropped, the atmosphere thinned and the prevalence of liquid water was reduced (either episodically or permanently), as a result of freezing of the water and reductions in total atmospheric pressure to below the triple point of water across large areas of the surface. During this time we can envisage a process of "synergistic decline." Through environmentally induced synergism, an accumulated increase in the importance of UV radiation as a detrimental factor would have occurred. Any potential biota on Mars would be forced into habitats in which these synergisms were minimized. This transition may have been continuous, or if the martian atmosphere suffered a collapse, rather sudden (Haberle *et al.* 1994). Through this environmental history we arrive at the present state, where the martian surface has DNA weighted irradiances that might have been similar to those of early Earth, at least under cloudless conditions, but in synergism with other extremes they result in a surface unsuitable for life and even for the persistence of organics (Stoker and Bullock 1997).

5. UV RADIATION ON PRESENT-DAY MARS—BIOLOGICAL 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* is a good model 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. Under 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 2 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 certain that from a raw soil sample, some species will 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 percentage loss of viability. Assuming that the microbes are not growing and that 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 be a problem, since there may well be nonlinear 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 do 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. 5.

To calculate the loss of viability of *B. 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.

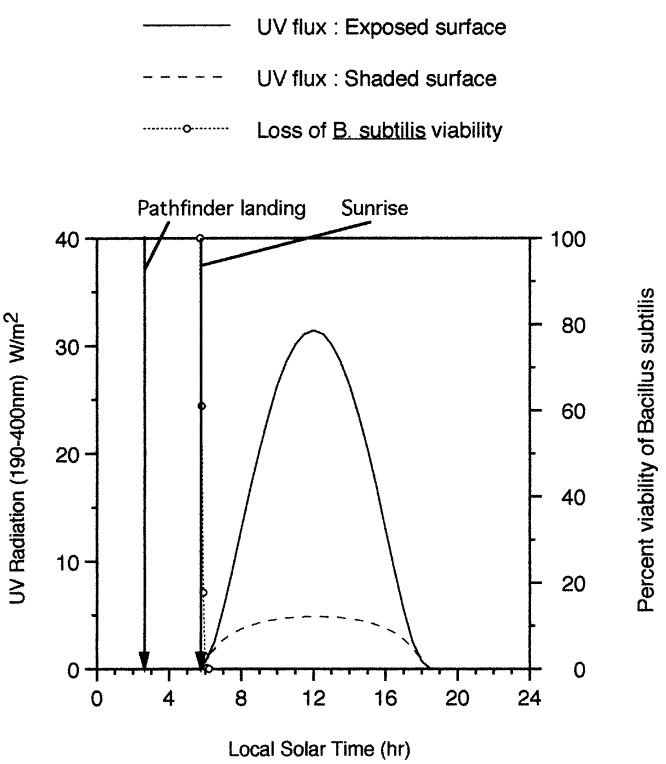

FIG. 5. UV flux on the day of the Pathfinder landing (4 July 1997). Data also show decline in *B. subtilis* viability associated with the exposed UV flux. Flux is shown for an exposed surface (direct plus diffuse UV) and for a shaded surface (diffuse only) ($\tau = 0.5$).

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 50 J/m^2 for spores in vacuum (3×10^{-6} mbar) at 298 K 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 fluence 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 subpopulation 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 h on the martian surface 1% still remain.

Sterilization could only occur 2 h 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 30 min less than 3% of the spores remain viable. 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 nearly the same rate as exposed surfaces.

Data are also shown for a theoretical polar lander in Fig. 6. Calculations assume landing on the arbitrary date of December 3, 1999, at 77°S. In Fig. 6a, data are shown for average dust loading ($\tau = 0.5$); for Fig. 6b, 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 2.68×10^{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 larger 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-h light cycle that spreads damage over the whole day. From a planetary protection viewpoint, the 24-h polar light cycle provides

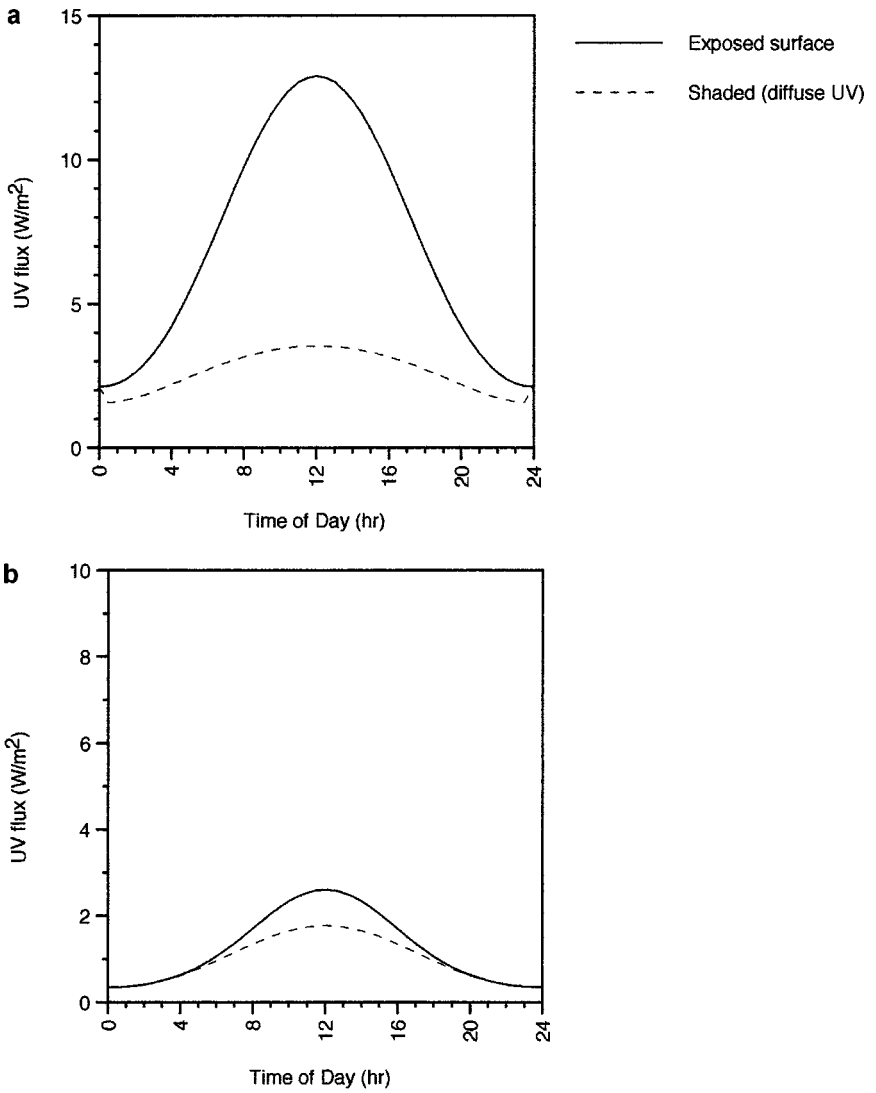

FIG. 6. UV flux at 77°S for a polar lander. Data presented is for a landing on 3 December 1999. Total daily fluence is about 76% of the UV fluence at the Pathfinder site. Flux is shown for an exposed surface (direct plus diffuse UV) and for a shaded surface (diffuse only). (a) Clear day with some dust loading ($\tau = 0.5$). (b) Medium-scale dust storm at the landing site ($\tau = 2.0$).

the opportunity for 24-h 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 min.

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 τ 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 μm and for a dust storm of $\tau = 6.0$, the thickness would be 10 μm. Using a thin layer ($\sim$100 μm) 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 will survive indefinitely until they are reexposed 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.

6. ALTERATION OF MARTIAN ATMOSPHERIC COMPOSITION—UV RADIATION ON FUTURE MARS?

The alteration of martian atmospheric conditions ("planetary engineering" or "terraforming") is a possibility that has been of interest for some time (Burns and Harwit 1973, McKay *et al.* 1991). The problem of the martian UV radiation flux for an unadapted and exposed terrestrial biota has been pervasive. From a theoretical standpoint it is of interest to investigate whether an artificial alteration of atmospheric parameters can indeed effect a significant alteration of the surface UV radiation regime.

i. Effects of CO_2 Release on UV Flux during the Warming of Mars

If Mars were warmed through the introduction of CFCs or other chemicals that increased the surface temperature, then the frozen CO_2 inventory of Mars would be released into the atmosphere (McKay *et al.* 1991). Five hundred millibars may be a conservative estimate for the martian inventory (McKay *et al.* 1991), although levels up to 3 bar are also possible as an upper limit of CO_2 availability (McKay *et al.* 1991).

In Fig. 7a, biologically effective doses for DNA damage (which also equates to microbial damage in many cases), generalized plant damage (Green *et al.* 1974), photosynthesis inhibition in phytoplankton (Cullen *et al.* 1992) and sunburn in mammalian skin (McKinlay and Diffey 1987) are shown as a function of CO_2 partial pressure. Heating of the polar caps and the surface will primarily increase CO_2, so only this component is factored into the atmospheric composition for the radiative transfer calculations. Increases in N_2 and O_2 might affect Rayleigh scattering, but in these cases, concentrations even with a 500-mb CO_2 atmosphere are likely to be less than 2–3 mb. The data are partly limited, since many of the action spectra do not

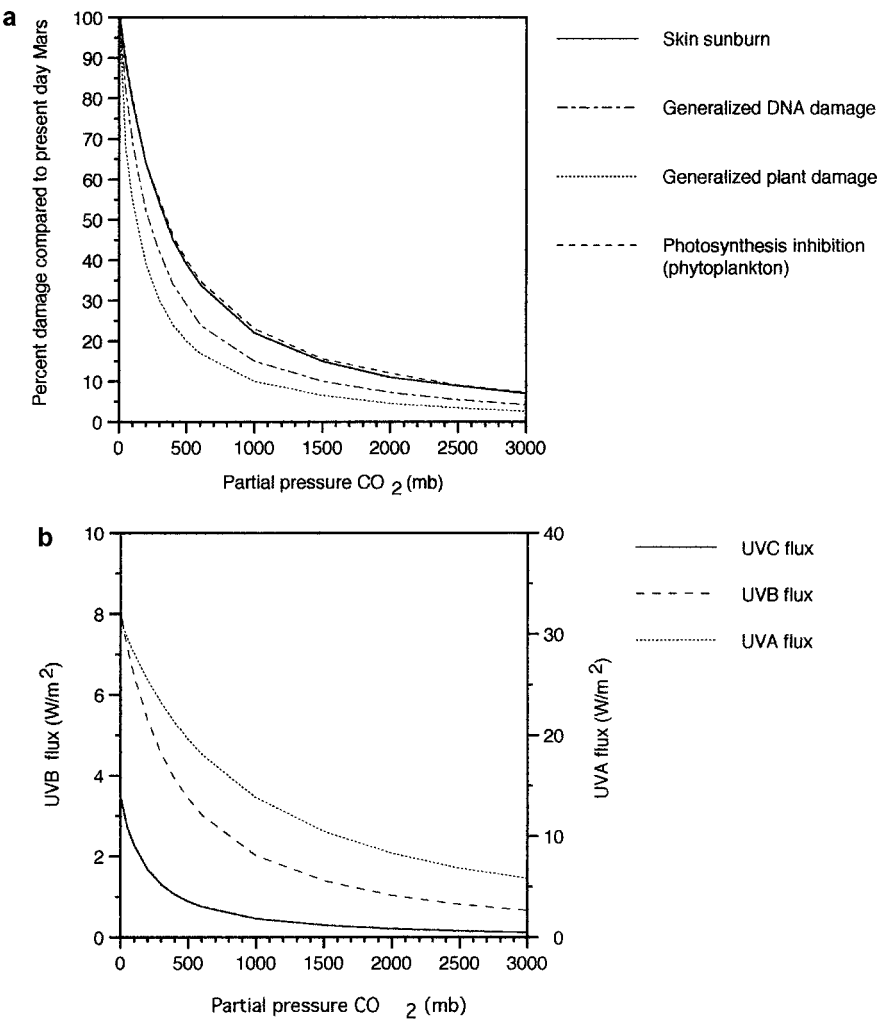

FIG. 7. (a) Reductions in biologically effective irradiances associated with increasing pCO_2 associated with the gradual warming and release of CO_2 on Mars. The present-day martian irradiances are defined as 100% damage and relative reductions are shown accordingly. Data are presented for vernal equinox and a solar zenith angle of 0° with $\tau = 0.1$. Note that the data for DNA also represents the photobiological effect of reducing CO_2 partial pressure on an evolving early Mars. (b) Reductions in UVA, B, and C associated with increasing pCO_2.

extend down to 200 nm (Fig. 3). However, all of them do extend into the UVB, whose reduction can also be considered a proxy for the reduction of UVC. The corresponding changes in UVA, B, and C caused by CO_2 scattering are shown in Fig. 7b. In all of these cases a dust optical depth of 0.1 and a zenith angle of 0° was taken in order to examine the protection provided in the worst-case exposure on a cloudless day.

The data in Fig. 7 indicate that the rise in CO_2 itself causes a significant reduction in UV flux, primarily due to scattering in the UVC and B regions. For an increase in CO_2 from present day values (6 mb) to 100 mb, biologically effective irradiances are broadly reduced by approximately 50 to 20% depending on the action spectrum considered. An increase to 500 mb reduces all biologically effective irradiances by at least 60% of present Mars values. If Mars possesses a higher CO_2 inventory (up to 2 bar) then the UV screen will be even more effective (Figs. 7a and 7b), although it can be clearly seen that the proportional reductions in UV radiation are less at increasing pCO_2 due to the correspondingly less effective scattering.

ii. Effects of an Ozone Shield on Martian Surficial UV Flux

The generation of O_2 in the martian atmosphere by a biota as well as abiotic production from photolytic reactions and increased atmospheric pressure (Rosenqvist and Chassefiere 1995) would result in the formation of ozone above the maximum 1.61×10^{17} cm^{-2} column density currently found at the martian north pole in winter (Barth *et al.* 1973). This has been suggested as a potential approach to reducing UV flux in terraforming considerations (Hiscox and Lindner 1997). In Fig. 8, the required global ozone column abundances are provided for various concentrations within the range that would bring biologically effective irradiances to within present-day Earth values.

For a 100-mb CO_2 atmosphere and taking the mid-point of the three action spectra shown in Fig. 8, where the damage is similar to that seen on present-day Earth, a shield of column abundance 6.5×10^{18} cm^{-2} will reduce the biologically effective irradiances sufficiently close to present-day Earth values. For a 500-mb CO_2 atmosphere, a 3×10^{18} cm^{-2} ozone column abundance reduces irradiances to present-day Earth values, and a minimum 2×10^{18} cm^{-2} column abundance may even suffice (four times less than typical equatorial Earth values). These column abundances might lie between a pO_2 of 1 and 20 mb based on existing terrestrial photochemical models (e.g., Kasting and Donahue 1980). Notice, however, that as CO_2 would be biotically drawn down and O_2 produced there would be a tradeoff between the less effective CO_2 scattering and the need for more ozone to increase UV screening.

iii. Alternative Approaches to Reducing UV Flux

Elemental sulfur is also a specific UV absorber (Kasting *et al.* 1989) and the sulfur content of martian rocks is approximately 2 wt%, similar for both Viking and Pathfinder analyses (Toulmin *et al.* 1977, Rieder *et al.* 1997). We introduced a sulfur haze into our radiative transfer calculations. Taking the mid-point of the three action spectra shown in Fig. 9, at which the damage is similar to that seen on present-day Earth, the injection of an elemental sulfur haze at a column density of 2.7×10^{17} cm^{-2} would reduce biologically effective irradiances down to present-day Earth values. This amount of sulfur is equivalent to an injection of 1.66×10^8 tons or 1.1 g/m^2. As pCO_2 is increased, so the

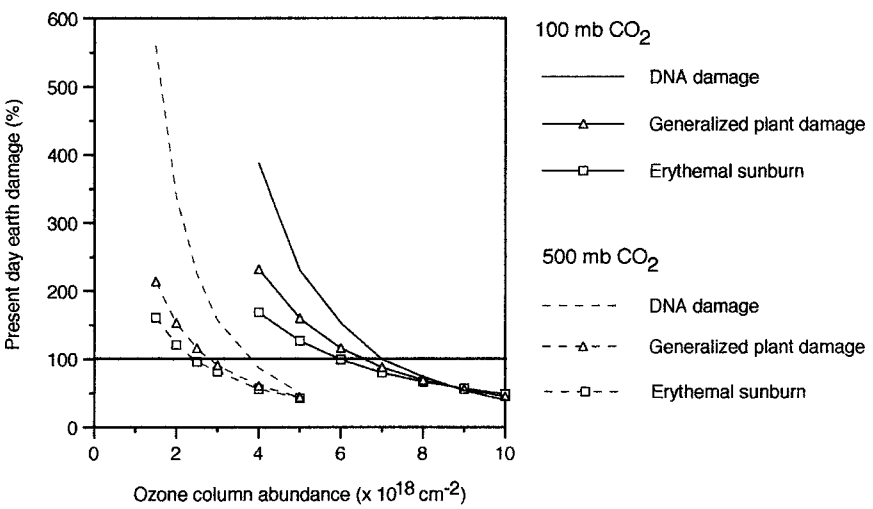

FIG. 8. Effect of increasing ozone column abundance on three selected biological processes in the presence of 100 mb and 500 mb CO_2. In contrast to Fig. 7, here values are shown as percentages in comparison to present-day Earth since absolute values of biologically effective irradiances are much lower. In all cases inhibition of phytoplankton photosynthesis was lower than present-day Earth values for the ozone concentrations shown. (Note that the present-day Earth DNA damage value (100% value) equals 0.1% of the damage that would be received on present-day Mars, plant damage equals 0.29%, phytoplankton photosynthesis inhibition equals 12%, and erythemal sunburn equals 4% for comparisons to Fig 7.)

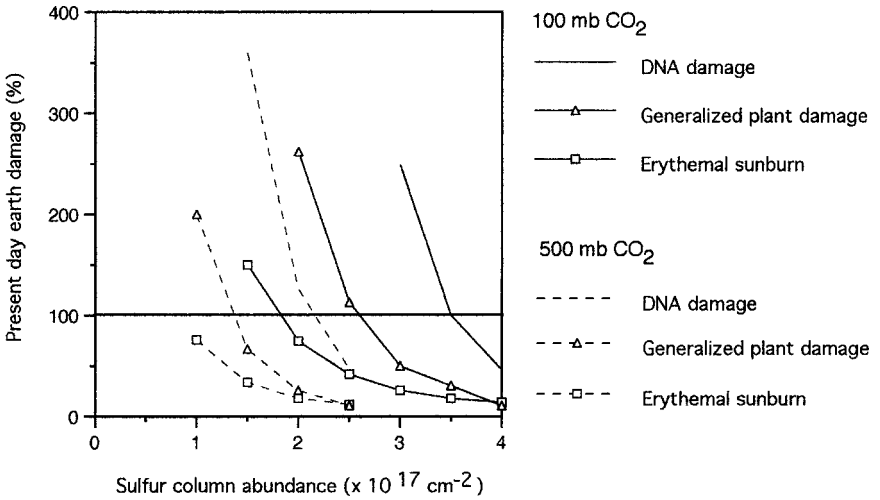

FIG. 9. Effect of increasing sulfur column abundance on three selected biological processes. Data is presented in an identical way to Fig. 8.

sulfur haze requirements are reduced because of the increased UV screening by CO_2. For a 500-mb CO_2 atmosphere the sulfur column abundance required is 1.7×10^{17} cm^{-2} (1.04×10^8 tons of sulfur) as shown in Fig. 9. One problem with sulfur is that on cold Mars temperatures in the high atmosphere would be below the saturation vapor pressures for sulfur vapor. Calculations showed that shield would work on early Earth only if the temperature were at least 45°C (Kasting *et al.* 1989). The shield would be more of an artificial sulfur particulate cloud. Furthermore, it may be subject to photochemical conversion to sulfuric acid. A more promising compound may be COS which also has a high cross section in the UVC region. However, the cross section is approximately three orders of magnitude lower than sulfur in the UVC and five orders of magnitude lower in the UVB range (Fig. 10). Using the cross section presented by Yung and Demore (1999), then a column abundance of greater than $\sim 10^{22}$ cm^{-2} would be required to reduce most weighted irradiances down to comparable values found on the surface of Earth.

A secondary advantage of sulfur derivatives, however, is that they provide a UV screen that is not destroyed by chlorofluorocarbons (CFCs). CFCs have been proposed as greenhouse gases to warm Mars (McKay *et al.* 1991). However, one of the major concerns has been that CFCs would destroy the ozone proposed for a UV screen. CFCs themselves are rather poor UV absorbers in the wavelengths of interest. In general, for most CFCs, absorbance cross-sections become significant at wavelengths <200 nm, although some may provide some screening at the lower end of the UVC range (e.g., DeMore *et al.* 1983). For example, CCl_3F has an absorption cross section of 1.5×10^{19} cm^{-2} at 210 nm, comparable to the ozone cross section at 305 nm. Other compounds with significant UV cross sections such as Cl_2O_2 or $ClONO_2$ (both with effective absorbances up to ~400 nm) (Yung and DeMore 1999) might also be considered, although photochemical models are required to predict their stability under different atmospheric regimes.

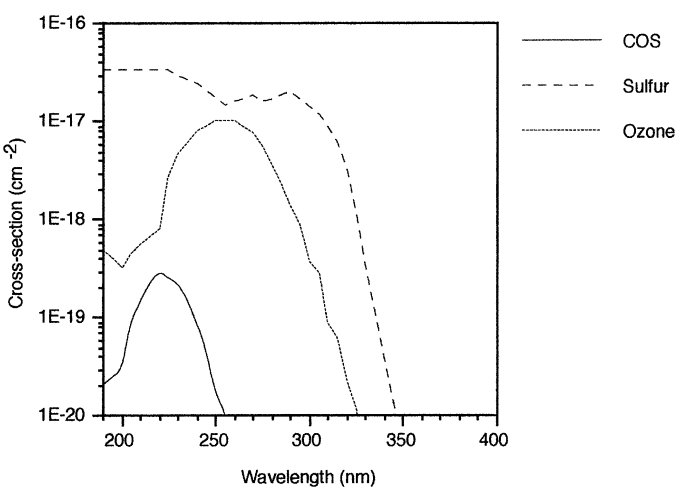

FIG. 10. Cross sections of the UV absorbers, COS, sulfur, and ozone.

7. CONCLUSIONS

The martian UV radiation environment has high UVB and UVC fluxes. The biologically effective irradiances of DNA inactivation and chloroplast (photosystem) inhibition on the martian surface can be estimated. Using terrestrial biology as a baseline, it is clear that the past martian UV radiation environment was probably not much worse than that on Archean Earth under cloudless skies. Many strategies seen on present-day Earth for mitigating UV flux can provide effective protection for biological systems on Mars. Even on present Mars, the UV flux is only slightly higher at a solar zenith angle of 0° than Archean Earth, although the accumulated damage could potentially be greater on Mars because of the longer day length. UV radiation, in synergism with reduced atmospheric pressure, the lack of liquid water, and the deterioration under other surface conditions on

Mars, would have become a contributory factor in the eventual demise of any possible life on the martian surface.

The early evolutionary photobiology of Earth is generally characterized by a period of steady UV flux in the Archean, then a reduction in flux from 200 to 290 nm as the stratospheric ozone column formed during the Archean–Proterozoic transition, such that biologically effective irradiances began to be drastically reduced, even with a 25% increase in solar luminosity superimposed. Although the Archean UV flux was clearly not a critical constraint to life, its later reduction must have made the surface of Earth considerably more clement. In contrast, the martian surface has probably seen a steadily increasing UV flux as a result of increasing solar luminosity and decreasing total atmospheric pressure which results in decreased UV scattering. These two photobiological histories must have had a significant comparative influence on a proposed evolutionary course for biological evolution.

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, care must be taken in qualifying the concept of a "sterilizing" UV flux, since the doses on Mars are probably not sterilizing when compared to those of early Earth and considered in an evolutionary context. Finally, UV flux may be significantly attenuated by increased atmospheric pressures of CO_2 in proposed artificial alterations of the atmosphere. These decreases in UV radiation would be improved by atmospheric ozone or by artificial UV screening compounds.

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