Europa’s surface radiation environment and considerations for in-situ sampling of endogenic material and detection of potential biosignatures

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Abstract

Jupiter’s moon Europa is one of the most compelling targets in the search for life beyond earth. Its geologically young surface, and a host of geologic surface features, indicate that material from the sub-surface may be emplaced on the surface. However, any material on the surface is bombarded by the harsh radiation environment of Jupiter’s magnetosphere, which over time may lead to chemical alteration and destruction of potential biosignatures. We have modelled the energetic particle bombardment at Europa and have investigated the interaction of these particles with material on the surface. Here we show that radiation processing and destruction of biologically relevant organics over the average surface age of Europa is expected to be significant down to depths of ~10 cm at low-latitude regions near the leading and trailing hemisphere apex, which are the regions that receive the highest radiation flux. Higher latitude regions away from these radiation ‘lenses’ experience nearly an order of magnitude reduction in radiation flux. These results indicate that potential future
missions to investigate the composition of endogenic material and search for potential biosignatures by sampling the shallow sub-surface of Europa could do so without the need to excavate material to large depths.

Main article

Jupiter’s moon Europa is considered a prime candidate in the search for life beyond Earth\(^1\). Its sub-surface ocean could host a biosphere sustained by chemical interactions with the rocky mantle and oxidants produced by radiation processing of water ice on Europa’s surface\(^2\text{-}^5\). While Europa’s ocean is covered by a thick ice shell\(^6\text{-}^10\) its young surface age of only 30 – 90 Myr\(^11,12\) indicates that global resurfacing processes have operated within geologically recent time. Highly disrupted surface regions may indicate locations where such active resurfacing has recently occurred, or is ongoing\(^9\), possibly due to melting of a thin ice shell from the ocean below\(^13\), or due to melting above a shallow meltwater lens\(^14\). Recently, evidence for transient water vapor plumes at several locations on Europa has been found in Hubble Space Telescope observations\(^15\text{-}^17\).

Emplacement of endogenic material onto the surface of Europa enables investigation of the chemical composition of the ocean and possibly other sub-surface liquid water regions. Importantly to the search for life, this also presents the opportunity to search for biosignatures with a robotic spacecraft on the surface without having to drill through Europa’s ice shell\(^18,19\). Within this context, it is important to consider that material on the surface of Europa will be exposed to the harsh radiation environment of the Jovian magnetosphere. The result of this interaction is that incident charged particles can break apart, rearrange, or otherwise modify chemical bonds in the surface and near-subsurface material, changing or even destroying the original source material. The extent to which surface material is affected by charged particle radiation depends
strongly on the depth beneath the surface to which material is buried, the type of material in which it is buried, and its geographic location on the surface of Europa\textsuperscript{20}. Of critical importance for potential biosignature detection, therefore, is to determine at which locations, and at which depths, one must sample in order to reach material that has not been significantly altered by charged particle bombardment, and which best represents the original composition of endogenic material.

Energetic electrons, which constitute >75\% of the incident energy from irradiation\textsuperscript{21}, do not bombard the surface of Europa uniformly and the access of electrons to a given surface location depends strongly on particle energy, as well as the local electromagnetic fields\textsuperscript{20,22,23}. For electrons, this is the primary factor in determining the radiation dose for a given surface location. Energetic ions, on the other hand, are expected to bombard the surface much more uniformly, due to their comparatively slow bounce times in Jupiter’s magnetic field, and large gyration radii relative to the size of Europa\textsuperscript{24–26}.

Here we have calculated the global bombardment pattern of energetic electrons using a previously developed\textsuperscript{22,27} bounce and gyration–averaged particle tracing method to determine access of electrons to different surface locations on Europa. Figure 1 shows the access of energetic electrons across the surface of Europa. For the trailing hemisphere, the values shown represent the highest energy in the electron distribution that can reach a given surface location. For the leading hemisphere, it shows the lowest energy electrons that may reach a given surface location. The reason for this is that the majority of electrons are of sufficiently low energy so as to be carried by Jupiter’s magnetic field, and are deposited on the trailing hemisphere, whereas the more energetic electrons (>20 MeV) experience a retrograde motion resulting in deposition
on the leading hemisphere. Not much is known about the electron spectrum at the highest energies, and electrons have only been directly detected at energies up to ~15 MeV\textsuperscript{28}. However, Jovian synchrotron emissions have been used to infer the presence of radiation belt electrons with energies of up to 100 MeV\textsuperscript{29}. If the effective upper limit is in fact lower than this energy, it is possible that the radiation environment on the leading hemisphere is less severe than the current modeling suggests.

The energy deposition for energetic electrons and protons for several surface locations was then simulated using a particle physics code that takes into account interactions of primary and secondary particles with surface material\textsuperscript{27}. This was done using representative electron and ion spectra at Europa’s location in the Jovian magnetosphere, as shown in Figure 2. The Jovian magnetosphere also contains significant populations of heavier ions, notably oxygen and sulfur ultimately originating from volcanic activity on the moon Io. However these heavy have very limited penetration range into the surface, at most on the order of millimeters\textsuperscript{30}, and are therefore not a dominant factor when considering the dose at depth. In all cases, the dose-depth profiles were calculated for unit density material (1 g cm\textsuperscript{-3}), which for Europa’s predominantly ice-covered surface is a reasonable initial assumption. The range of charged particles in a material depends strongly on the number of electrons per volume of that material, so the presence of salts and other higher density materials would lead to shallower penetration depths, and lower density, more porous materials would lead to deeper penetration depths.

Shown in Figure 3 is the depth-resolved energy deposition for several representative locations on the surface of Europa. This is given in terms of time to reach a significant radiation dose of 100 eV/16 amu at a given depth into the surface. This
A dose is a common standard in laboratory irradiation studies and represents the dose at which any chemical bond in the material would have received enough energy to have been destroyed several times (the sigma and pi bonds of carbon, for example, have an energy of <10 eV). This dose, which corresponds to approximately 600 MGy, represents a reasonable value for considering radiolytic steady-state. Importantly, as is known from uranium-rich shales on Earth and the Archean rock record, radiation does not serve to destroy everything—some chemical bonds (e.g., carbonyl, nitrile, and some aromatics) are much more robust to radiation than others.

Material in the uppermost (~ few cm) surface near the equator on the trailing hemisphere experiences the highest radiation doses anywhere on Europa. This is because the flux tubes carrying the majority of lower energy, but abundant, electrons empty as the field lines intersect Europa’s trailing hemisphere apex. At low latitudes on both hemispheres, the timescales for accumulating a dose of 100 eV/16 amu are on the order of, or shorter than, the average surface age, down to depth of approximately 10 cm. The dose at centimeter depths in these locations is dominated by energetic electrons in the MeV energy range and their secondary particles (mostly bremsstrahlung photons). By comparison, locations at latitudes above 40° on the trailing hemisphere are only bombarded by lower energy (E < 250 keV) electrons, which have a penetration range of less than a millimeter into surface ice. The dose at greater depths in this region is therefore dominated by protons that are not capable of penetrating as deeply as the electrons. For example, the penetration range of a 50 MeV proton is only expected to be on the order of ~2 cm in water ice. High latitude locations above 45° on the leading hemisphere are only bombarded by the most energetic population of energetic electrons (E > 40 MeV) that have a penetration range into the surface ice of tens of centimeters, yet are only present at a relatively low flux. As a result, surface material there is less...
irradiated, and experiences a lower total dose over the surface lifetime, than at low
latitudes. The dose at near-polar (>65°) latitudes on the leading hemisphere is
dominated by the energetic protons and the radiation processing timescales there are
comparable to those of the high latitude trailing hemisphere. The less irradiated regions
at the leading and trailing hemispheres extend to lower latitudes as one moves away
from the apex meridians at 90°W and 90°E. The net result of these components of the
radiation geography on Europa’s surface is a trailing hemisphere ‘lens’ and a leading
hemisphere ‘lens’ where the total dose as a function of time and depth into the surface
is considerably higher than at other regions.

Earlier preliminary work considered charged particle interactions with surface
material only at the low latitude apex points at either hemisphere²³,³⁰, leading to the
misconception that the trailing hemisphere of Europa, as a whole, is the most irradiated.
Based on our results from modelling charged particle interactions with surface ice at
numerous locations across the surface of Europa we show that the high (> 40°) latitude
trailing hemisphere and the near-polar (> 65°) leading hemisphere provide the most
benign radiation environment in terms of energetic charged particle bombardment at
depth. At these locations, sampling below the top ~cm of surface material should be
sufficient to reach material that is largely unaltered by charged particle processing over
timescales of ~10 Myr. Identification of regions of a younger surface age would further
reduce this radiation processing depth. Within the equatorial lens regions however, the
radiation processed regolith extends down to 10 cm over ~10 Myr timescales, but again,
younger terrains may present the opportunity for sampling at significantly shallower
depths even in these ‘worst case’ geographic regions on Europa. Shown in Figure 4
(blue ovals) are the surface locations where magnetospheric radiation processes material down to 10 cm depths over timescales of 10 Myr.

It should be noted that the surface of Europa is also exposed to Galactic Cosmic Rays (GCRs). While these particles are highly energetic, their flux is very small compared to that of trapped magnetospheric particles. For comparison, the GCR dose calculated for unit density water ice on Mars is lower than the calculated radiation dose due to magnetospheric particles within the top 1 m at all locations on Europa; in other words, the jovian radiation environment is more severe than that due to the background GCR flux. In addition, the Jovian magnetosphere provides some shielding from GCRs at Europa’s position, such that the actual GCR dose at Europa will be somewhat lower than the comparable dose at the same depth on Mars. Finally, and perhaps most significantly, we note that the surface age of Europa is one to two orders of magnitude younger than much of the surface of Mars, which leads to a corresponding reduction in total accumulated dose, and depth of radiation processing.

On Europa our results (c.f. Figure 3) show that surface material down to mm depths reaches a Grad level dose on timescales of < 1 kyr in most locations. In the context of biosignature detection and preservation of organics it is therefore important to quantitatively evaluate the destruction of candidate materials as a function of depth and location on Europa’s surface.

Here we have considered the destruction of amino acids as a case study for potential biosignature destruction via radiolysis on Europa. Amino acids are not strictly a sign of life but they could serve as one of the simplest molecules that qualifies as a potential biosignature. While amino acids have a variety of biogenic and abiotic
formation mechanisms, they are useful compounds to use as an example for survival in high radiation environments. Amino acids are the building blocks for proteins and they have been well-studied in the context of survival on Mars and other targets of astrobiological interest.

Early laboratory studies of irradiated amino acids considered pure dehydrated samples at room temperature and found that the radiolysis constant (the rate of destruction given a specified radiation dose) increases roughly linearly with the molecular weight\(^{39,40}\). Subsequent laboratory studies found that amino acid destruction rates tend to increase modestly at lower temperatures such as those relevant to the surface of Europa and other icy bodies\(^ {41,42}\). Importantly, these studies also found that amino acids contained within water ice at low temperatures display significantly reduced destruction rates compared to pure samples of anhydrous amino acid. Here we have made use of published amino acid destruction rates in water ice\(^ {42}\) to estimate the expected destruction timescales and survival fraction of amino acids (specifically glycine, alanine, and phenylalanine) on the surface of Europa and within its shallow subsurface. Shown in Figure 5 are the amino acid destruction rates and survival fraction (\(N/N_0\), where \(N_0\) is the initial amino acid concentration and \(N\) is the final concentration) as a function of depth calculated for two different radiation exposure ages. The first case (1 kyr) represents a situation where the surface is being actively replenished, e.g. due to emplacement of fresh material at chaotic terrain or through deposition of plume material. The second case (10 Myr) represents a scenario where material is exposed to the near-surface radiation environment over the average surface age of Europa. For the 1 kyr case radiolytic destruction of amino acids is negligible below the top ~mm of the surface for all regions except the trailing hemisphere apex. In that region, there is a reduction to approximately 10% of the initial amino acid concentration in the uppermost
millimeter over the course over this timescale. At depths greater than ~1 cm the survival
fraction remains near unity. As surface exposure time increases, the geographic
influence of particle irradiation becomes increasingly apparent. For the 10 Myr case,
amino acid destruction varies very strongly with surface location on Europa (plots for
exposure times between 1 kyr and 10 Myr can be found in the Supplementary Materials,
Figure 2). At high latitudes on either hemisphere, destruction rates fall off very rapidly
at ~cm depths. A reduction to 10% of the initial concentration is reached at
approximately 6 mm below the surface in the trailing high latitude regions, while in the
leading high latitude regions a comparable reduction is achieved at approximately 8 cm.
By comparison, low latitude locations achieve a comparable reduction in the initial
concentration at nearly a 10 cm depth over the 10 Myr surface lifetime. In other words,
organics such as amino acids are more likely to survive for long periods at shallow
depths in surface locations that are at higher latitudes, with the most benign region being
that of the trailing high latitude region, followed by the leading high latitude region.
Importantly, these results also show that the majority of the initial amino acid
concentration survives for well over 10 Myr timescales at 10 cm depths in even the
harshest of radiation environments on the surface of Europa. Future efforts to sample
less-processed surface materials should prioritize the higher latitude regions of Europa,
and regions determined to be young (<10 Myr) in surface age.
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Author contributions

TAN carried out the modeling of energetic electron and proton interactions at the surface of Europa as well as calculation of amino acid destruction rates. CP provided fit functions for the electron and proton spectra at Europa as well as guidance on the modeling of energetic electron access to Europa’s surface. KPH provided overall guidance on the execution of the research as well as providing key inputs on the discussion of biosignature destruction at Europa.
References


Figure 1 - Energetic electron bombardment patterns for the surface of Europa.

At the leading hemisphere (top), the cut-off energy represents the lowest energy electrons capable of accessing a region on the surface. At the trailing hemisphere
(bottom), the cut-off energy represents the highest energy electron capable of accessing a region on the surface.

Figure 2.

Figure 2 – Representative electron and proton particle flux spectra at Europa.

These energetic particle flux spectra were produced according to fits to measurements made by the Voyager 1 LECP and the Galileo EPD and HIC instruments$^{22,30}$. 
Figure 3 – Timescales for the accumulation of a significant radiation dose at different depths for several locations on the surface of Europa. The energetic electron dose is given in terms of years to reach a significant dose of 100 eV/16 amu, which is equal to a dose of 603 MGy. Dose-depth profiles in dosage units are provided in Supplementary Materials Figure 1.
Figure 4. – **Radiation processing map of Europa’s surface.** In blue, locations where magnetospheric radiation has processed surface material down to a depth of 10 cm. Here we have considered material to be processed if they have received a dose of 100 eV/16 amu in less than 10 Myr.
Figure 5 – **Destruction of amino acids within Europa surface material for young** (left, 1 kyr) and old (right, 10 Myr) surface material. The quantity on the y axis represents the fraction of remaining amino acid given the radiation dose sustained over that timescale.
Methods

Here we assume that the gyroradius of the electrons is negligible compared to the size of Europa – for a 1 MeV electron with a pitch angle of 45° the gyro-radius ($R_g$) is $<< 1\%$ of Europa’s radius. The bounce-averaged longitudinal distance (expressed as a fraction of Europa’s radius) that an electron can travel across Europa before being absorbed may therefore be approximated by,

$$d(E, \lambda_m) = \omega L \left( \frac{t_b(E, \lambda_m)}{2} \right) \left( \frac{R_{\text{Jupiter}}}{R_{\text{Europa}}} \right)$$

where $\omega$ is the particle’s net azimuthal drift rate around Jupiter, $L$ is the dimensionless L-shell at the location of Europa (9.4 $R_{\text{Jupiter}}$), $t_b$ is the particle’s bounce time between magnetic mirror points and $R_{\text{Jupiter}}$ (71492 km) and $R_{\text{Europa}}$ (1560.8 km) are the radii of Jupiter and Europa, respectively. The azimuthal drift rate $\omega$ is given by

$$\omega = f_c(L) \Omega_{\text{Jupiter}} + \omega_{\text{GC}}(L, E, \lambda_m) - \omega_{\text{Europa}}$$

where $\Omega_{\text{Jupiter}}$ is the rotation rate of Jupiter, $f_c(L)$ represents the corotation fraction at Europa’s L-shell, $\omega_{\text{GC}}$ is the gradient-curvature drift rate in the corotating frame of Jupiter and $\omega_{\text{Europa}}$ is the angular rate of the Europa’s motion around Jupiter in inertial space. The parameters $t_b$ and $\omega_{\text{GC}}$ are calculated following the method of $^{43}$ which assumes a dipole magnetic field. These calculations assume a corotation fraction $f_c$ that is 0.8 of rigid corotation, which is consistent with Galileo Plasma Science Instrument measurements near Europa’s L-shell$^{44,45}$. For each point $P(\theta, \phi)$ on the surface of Europa we calculate the projected distance $d_P$ from the equatorial plane.
\[ d_p = R_{Europa} \left( 1 + \sin^2 \theta (\cos^2 \varphi - \sin^2 \varphi) - 2 \sin \theta \cos \varphi (1 - \sin^2 \theta \sin^2 \varphi)^{1/2} \right)^{1/2} \]

as previously described by \(^{20}\) and \(^{27}\). By comparing the value of \(d_p\) to the calculated value \(d(E, \lambda_m)\) we evaluate particle access to that location on the surface.

The electron spectrum at the orbit of Europa (Figure 2, blue curve) was implemented according to the following fit function based on observations by the Low Energy Charged Particle (LECP) instrument during the Voyager 1 flyby and the Energetic Particle Detector (EPD) instrument Galileo E12, E14 and E26 flybys.

\[ j(E) = j_0 E^a \left( 1 + \frac{E}{E_0} \right)^{-b} \]

, where \(j\) is the intensity at electron energy \(E\) and the fit parameters are \(j_0 = 4.23, E_0 = 3.11, a = -1.58\) and \(b = 1.86^{22}\).

The proton spectrum at the orbit of Europa (Figure 2, red curve) was implemented according to the following fit function based on observations made by the EPD and Heavy Ion Counter (HIC) instruments during the Galileo E12 flyby that represents Europa when it is near the center of the Jovian current sheet and thus in a particularly harsh radiation environment. The fit function used to represent this spectrum takes the form

\[ j(E) = cE(E + kT(1 + \gamma))^{-1-\gamma_1} \times \left( 1 + \left( \frac{E}{E_T} \right)^{\gamma_2} \right)^{-1} \]
where \( j \) is the intensity at proton energy \( E \) and the variables  
\[
C = 842.79, kT = 0.03, \gamma_1 = 1.36, \gamma_2 = 4.78 \text{ and } E_r = 10414.25^{30}.
\]

The interaction of charged particles with the surface of Europa was simulated using the PLANETOCOSMICS application\(^{46}\), which is based on the Geant4 toolkit\(^{47}\). The simulations were implemented according to the method of \(^{27}\). For each point on the surface, the energy cutoff for the electrons is calculated according to the formula for \( d \) given above. The input spectrum for the simulation was then modified to account for the fraction of electrons capable of reaching that surface location. We approximate the proton dose by assuming that protons are capable of reaching all surface locations on Europa. To first order this is a reasonable assumption as proton bounce times, particularly at MeV energies, are much longer than the time it takes for them to drift across the surface of Europa in the longitudinal direction\(^{23}\). In addition, the gyro-radii of energetic protons at Europa are much larger than those of the equivalent energy electrons (e.g. for a 1 MeV proton with pitch angle 45, \( R_g \) is \( > 0.1 \) \( R_{Europa} \)). The surface was represented as a flat slab of H\(_2\)O with a density of 1 g cm\(^{-3}\).

The destruction rate of amino acids was calculated using the exponential function  
\[
\ln \left( \frac{N}{N_0} \right) = -kD
\]
where \( N \) is the fraction of amino acid abundance after radiation, \( N_0 \) is the amino acid abundance prior to radiation, \( D \) is the radiation dose in MegaGrays (MGy) and \( k \) is the radiolysis constant in units of of MGy\(^{-1}\). We have used a radiolysis constant based on previous laboratory experiments on proton irradiation of Glycine, Alanine and Phenylalanine that is incorporated in cryogenic H\(_2\)O ice samples\(^{42}\). Based on the individual radiolysis constants that these authors reported for experiments at 100 K
we have calculated a mean radiolysis constant of 0.0135 MGy$^{-1}$ for amino acids contained within water ice at this temperature. That work utilized samples that included a relatively large fraction of amino acid to H$_2$O ice and therefore represents a conservative estimate. This radiolysis constant yields destruction rates versus depth as shown in the manuscript in Figure 5 of the main manuscript and in Supplementary Materials Figure 2.
Supplementary Materials Figure 1 – Calculated dose-depth curves for energetic particles bombarding the surface of Europa at four different locations: The trailing hemisphere apex (N 0°N, 90°E), leading hemisphere apex (red: 0°N, 90°W), high latitude locations on the trailing hemisphere (black: >45° N/S, 90°E), and high latitude locations on the leading hemisphere (green: 35°, 90°W). Plot colors correspond to those shown in Figures 3 and 5 of the main manuscript.
Supplementary Materials Figure 2 – Destruction of amino acids within the near-surface of Europa for six different surface exposure ages. The quantity on the y axis represents the fraction of remaining amino acid given the radiation dose sustained over that timescale. Assumes a mean radiolysis constant of 0.0135 MGy\(^{-1}\) for amino acids contained within samples of H\(_2\)O ice at a temperature of 100 K\(^{42}\).