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Fluorescent Biomolecules Detectable in Near-Surface Ice on Europa

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Abstract

Europa, Jupiter's second Galilean moon, is believed to host a subsurface ocean in contact with a rocky mantle, where hydrothermal activity may drive the synthesis of organic molecules. Among these possible organic molecules, abiotic synthesis of aromatic amino acids is unlikely, so their detection on planetary surfaces such as Europa suggests that they could be considered a potential biosignature. Fluorescence from aromatic amino acids, with characteristic emissions in the 200–400 nm wavelength range, can be induced by a laser and may be detectable where ocean material has been relatively recently emplaced on Europa's surface, as indicated by geologically young terrain and surface features. However, surface bombardment by charged particles from the jovian magnetosphere and solar ultraviolet (UV) radiation degrades organic molecules and limits their longevity. We model radiolysis and photolysis of aromatic amino acids embedded in ice. Our model shows dependencies on hemispheric and latitudinal patterns of charged particle bombardment and ice phase. We demonstrate that such molecules contained within freshly deposited ice in high-latitude regions on the surface of Europa are detectable using laser-induced UV fluorescence, even from an orbiting spacecraft. Key Words: Europa (moon)—Amino acids—Spectroscopy. Astrobiology 25, 359–366.

1. Introduction

Europa is a prime candidate in the search for extraterrestrial life due to its subsurface ocean, believed to be in contact with a rocky mantle (Carr et al., 1998). Hydrothermal activity on the ocean floor, driven by tidal heating, could support serpentinization, which would generate hydrogen and synthesize organic molecules from inorganic precursors (Zolotov and Shock, 2001). The generation of hydrogen through serpentinization is particularly significant because it provides a crucial ingredient for the synthesis of organic molecules (Wang et al., 2014) and could potentially fuel a subsurface biosphere. These processes mirror early Earth conditions where hydrothermal systems may have been a potential setting for the origin of life by providing energy and essential building blocks for complex organic chemistry (Martin et al., 2008).

Aromatic amino acids, namely phenylalanine, tyrosine, and tryptophan, are particularly intriguing in the search for extraterrestrial life. These molecules are essential for life as they play critical roles in cellular processes, including protein synthesis and enzyme function (Pittard and Yang, 2008). Their unique structures, which feature benzene or indole rings, enable them to absorb UV light and fluoresce distinctly in the 200–400 nm range (Beaven and Holiday, 1952). This fluorescence makes them valuable as unique tracers in fields such as medicine and biochemistry (Yamashita and Tanoue, 2003), as well as within the context of the origin of and search for life (Ehrenfreund et al., 2006). The fluorescence of aromatic amino acids is utilized for their detection in aquatic and icy settings on Earth (Eshelman et al., 2019), as well as in planetary contexts, where, for example, the Scanning Habitable Environments with Raman & Luminescence for Organics & Chemicals (SHERLOC) instrument (Beegle et al., 2015) aboard the Perseverance rover on Mars utilizes deep ultraviolet (DUV) laser-induced fluorescence to detect and analyze organic compounds and minerals on the martian surface (Bhartia et al., 2021). Similar conceptual frameworks

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have been proposed for more extreme settings of solar system exploration, such as *in situ* or remote laser-induced spectroscopic analysis of meteorites (Lymer et al., 2021).

Simple amino acids such as glycine and alanine have been detected in various abiotic settings, including carbonaceous chondritic meteorites (Pizzarello et al., 1991) and hydrothermal environments (Zhang et al., 2017), where the Strecker synthesis is a well-established generation pathway (Koga and Naraoka, 2022). In contrast, the synthesis of aromatic amino acids, with their more complex molecular structures, typically relies on multi-enzymatic metabolic pathways, such as the Shikimate pathway, which converts simple carbohydrates into aromatic compounds (Maeda and Dudareva, 2012). The rarity of non-biological pathways for production of aromatic amino acids has led to the proposal that such molecules are compelling biosignatures (Georgiou, 2018).

The recent detection of 14 out of the 20 proteinogenic amino acids, including tentative evidence for aromatic amino acids, in samples returned from asteroid Bennu expands the possibilities of prebiotic chemistry that occurred in the protosolar disk (Glavin et al., 2025). The presence of these compounds, formed through a combination of photochemical, radiolytic, and aqueous processes in ammonia-rich conditions, suggests that complex organic synthesis can take place in the early solar system and broadens our understanding of the chemical precursors available for the emergence of life. Notably, polycyclic aromatic hydrocarbons (PAHs), which are structurally complex organic molecules composed of multiple aromatic rings, can also form abiotically through photochemical processing on surfaces such as water ice or silicate grains in stellar systems and protoplanetary disks (Henning and Semenov, 2013; Kahan and Donaldson, 2007; Noble et al., 2020). PAHs exhibit fluorescence similar to aromatic amino acids and produce distinct near- and mid-infrared emission features (Aihara, 1992; Peeters et al., 2021), which makes them valuable tracers of organic chemistry in extraterrestrial environments (*e.g.*, Giese et al., 2022; Xu et al., 2024). Their presence, alongside amino acids in Bennu's pristine material, underscores the diversity of prebiotic organic molecules that could have been available during planetary formation and the early evolution of life.

On Earth, a marginal detection of tryptophan in the Lost City hydrothermal field represents the only known case where the synthesis of aromatic amino acids has been suggested to occur through an abiotic process (Ménez et al., 2018). Barring contamination from biological sources, this discovery is significant, as similar hydrothermal vent systems may exist on Europa. These environments could offer conditions conducive to the synthesis of complex organic molecules via both biotic and previously unexplored abiotic mechanisms in the extant solar system (Lang and Brazelton, 2020).

Recently, a novel probabilistic approach introduced the molecular assembly index (MA), a measure that quantifies the assembly complexity of molecules (Marshall et al., 2021). According to this measure, molecules with an MA score greater than 15 are extremely unlikely to form abiotically. Tyrosine and tryptophan have MA scores of 10 and 12, respectively, as opposed to glycine, for example, which has an MA score of 4. Thus, while the abiotic synthesis of the aromatic species is possible, it is not likely, which further elucidates the dearth of discovery of these species in abiotic settings. On Earth, the concentration of tryptophan has been measured to be about 0.1 part-per-billion (ppb) in the barren regions of the well-mixed ocean, where its synthesis is least likely (Yamashita and Tanoue, 2004). The average abundances of tyrosine and phenylalanine are about 36 and 66 times higher, respectively (Moura et al., 2013). While the observed concentrations cannot be directly tied to specific synthesis mechanisms, we consider them a conservative estimate for the initial concentration of aromatic amino acids in a well-mixed europan ocean that contains putative life.

The detection of salts and ocean-derived compounds on Europa's surface suggests that subsurface material may be reaching the surface (Zolotov and Shock, 2001). Recent James Webb Space Telescope (JWST) observations of carbon dioxide, its spatial distribution pattern, and isotope ratios also indicate an internal source of carbon (Trumbo and Brown, 2023; Villanueva et al., 2023), which further supports this hypothesis.

Several mechanisms could transport material from Europa's subsurface ocean to its surface. Cryovolcanism can deposit ocean material on the surface (Sparks et al., 2017), while tectonic activity can create pathways for subsurface material to ascend (Cashion et al., 2024). Diapirism may also transport ocean material upward with buoyant ice (Pappalardo and Barr, 2004). Of these mechanisms, plumes are especially intriguing. Observations from the Hubble Space Telescope and Galileo spacecraft suggest that water vapor plumes erupt from Europa's surface and potentially deposit oceanic materials onto the ice (Roth et al., 2014)—a process that is more frequent and better understood on Enceladus (Postberg et al., 2011). This mechanism of emplacing ocean material onto the surface bypasses many complexities associated with other mechanisms, whose efficiency and timescales are not well constrained, and may involve significant alteration or mixing of the transported material during its ascent (Travis et al., 2012).

Lastly, the detectability of these molecules is influenced not only by the rates of their delivery to the surface but, importantly, by their longevity in the harsh surface environment. The europan surface experiences intense radiation due to electrons and ions from Jupiter's magnetosphere (Nordheim et al., 2018, 2022), whose penetration depth depends primarily on the particles' kinetic energy and can range between nanometers up to nearly a meter, and solar UV radiation, whose penetration depth varies similarly by many orders of magnitude, from millimeters to meters, depending on the optical properties of the ice (Johnson et al., 2012; Orzechowska et al., 2007). These processes, in turn, depend on the ice's thermal state and history (He et al., 2022), irradiation intensity (Strazzulla et al., 1992), and additional processes that are stochastic on short time scales ($<10^3$ years), such as impact gardening (Costello et al., 2021). We modeled the radiolytic and photolytic degradation mechanisms independently and subsequently combined them to estimate the integrated longevity of aromatic amino acids embedded in europan near-surface ice.

2. Modeling Degradation Mechanisms

2.1. Radiolysis

Studies of the jovian magnetosphere, specifically at Europa's orbital distance (Mauk et al., 2004; Nordheim et al., 2022;

Paranicas et al, 2001), have highlighted key aspects of the charged particles that impact Europa, specifically: (1) charged particles span kinetic energies from approximately 10 KeV to 100 MeV (Nordheim et al., 2018), where high kinetic-energy particles are much sparser than low kinetic-energy particles. (2) Major ions bombard Europa's surface relatively uniformly (Nordheim et al., 2022). (3) Energetic electrons exhibit a strong latitude- and hemisphere-dependent pattern. Electrons with kinetic energies below $\sim$20 MeV drift faster than Europa's orbital velocity and thus impact the trailing hemisphere. More energetic electrons, which are scarcer, impact the leading hemisphere because they have net retrograde drifts relative to Europa's orbital motion (Nordheim et al., 2018). As a result, electron bombardment patterns form radiation "lenses" focused on the equatorial regions and extend to the mid-latitudes (Nordheim et al., 2018).

We implemented a simplified approach to simulate the interaction of charged particles with near-surface ice, utilizing methods similar to those used in previous studies (Nordheim et al., 2018) (see Supplementary Appendix A). Our model accounts for electrons and the three most abundant magnetospheric ions near Europa's orbit: H^+, O^{2+}, and S^{3+} (Nordheim et al., 2022). Although there is some uncertainty regarding the charge states and their distribution among magnetospheric ions, our selection of these ions is primarily based on observational data (Mauk et al., 2004). To simplify the simulation process, we assumed a uniform bombardment pattern for the ions. While additional factors, such as an ocean-induced magnetic field (Kivelson et al., 2004), could be included, it has been shown that their impact on the bombardment pattern is relatively minor (Nordheim et al., 2022) and adds significant complexity to the simulation. Moreover, deviations from uniform ion bombardment are most pronounced in low-latitude regions where electron energy deposition peaks; thus, the effect of this non-uniformity is small when the total surface dose from all charged particles is considered (Nordheim et al., 2022). The surface was modeled as pure water ice with a density of 0.5 g/cm^3, incorporating the effects of porosity. This density is consistent with an expected porosity of approximately 0.3–0.5 for vapor-deposited water ice under europan conditions (Mitchell et al., 2017).

To compute the longevity of amino acids under charged particle bombardment on Europa, we used a radiolytic constant of 0.034 MGy^{-1} for a mixture of tryptophan, phenylalanine, and tyrosine, based on experimental values and scaled radiolytic reaction rates (Cataldo et al., 2011; Gerakines et al., 2012) (see Supplementary Appendix A). The radiolytic constant can exhibit considerable variability that depends both on surface conditions and the distribution of the organic material (Gerakines et al., 2012; Pavlov et al., 2024). For example, hydrated salts on Europa's surface, such as magnesium sulfate ($MgSO_4 \times nH_2O$), can absorb radiation, which could reduce the formation of radiolytic products and could stabilize amino acids against degradation over geological timescales (Brown and Hand, 2013; Carlson et al., 1999). Additionally, recent experiments have demonstrated that amino acids within organic matter degrade much slower than free amino acids in ice. This suggests their longevity may be significantly extended under realistic europan conditions (Pavlov et al., 2024).

Electrons that bombard the trailing hemisphere are considerably more numerous but less energetic ($\lesssim$ 20 MeV), which results in the deposition rate of more than an order of magnitude more energy into the ice. Furthermore, these less energetic electrons exhibit smaller penetration depths, which leads to increased radiolytic degradation of amino acids within the upper layers. Although energetic ions are sparser, they are also effective at degrading amino acids in the near-surface ice, because the two heavier ions deposit most of their energy within the top layer of the near-surface ice, in contrast to electrons, which tend to penetrate deeper (a detailed discussion can be found in Supplementary Appendix A).

2.2. Photolysis

The photolytic degradation of amino acids can be approximated as a first-order exponential decay process influenced by wavelength-dependent photolytic reaction rates (Johnson et al., 2012) (see Supplementary Appendix B). We considered the spectral range for photolysis to be between 147 and 342 nm, where the lower limit of 147 nm was chosen based on experimental evidence that indicated significant attenuation of photons by water ice below this wavelength (He et al., 2022; Warren, 2019), while the upper limit corresponds to the dissociation energy of the C_α–C_β bond in glycine (about 3.62 eV; Luo, 2002) (see Supplementary Appendix B). Reaction rates for phenylalanine were extrapolated from measured values under equatorial surface conditions on Europa (Johnson et al., 2012), and the rates for tyrosine and tryptophan were adjusted to reflect differences caused by molecular structure, as observed in γ-ray radiolysis experiments (Cataldo et al., 2011) (a detailed discussion about the photolytic spectral range and reaction rates can be found in Supplementary Appendix B). The annual mean solar flux incident on Europa's surface was calculated by accounting for the latitudinal dependence, Europa's time in Jupiter's shadow and its disk-averaged albedo; and the attenuation of this radiation with depth in the ice was modeled using a Beer-Lambert decay law, governed by ice extinction (see Supplementary Appendix B).

Amorphous solid water (ASW) is considered a characteristic phase of near-surface ice on Europa, especially in high-latitude regions (Hansen and McCord, 2004), maintained by mechanisms such as impact gardening (Mastrapa et al., 2013) and slow crystallization time scales (Mitchell et al., 2017). Recently, wavelength-dependent extinction coefficient profiles of vapor-deposited ice, in both amorphous and crystalline phases, were measured under different deposition temperatures and shown to exhibit significant backscattering in the UV-visible range (He et al., 2022). Additionally, it was shown that post-deposition heating changes the optical properties of amorphous vapor-deposited ice, often increasing the extinction coefficient by more than an order of magnitude (He et al., 2022). This is significant because photolytic degradation of amino acids by solar UV photons is potent when they are embedded in polycrystalline ice, which is nearly transparent at UV-visible wavelengths (Warren, 2019), and results in very short half-lives of amino acids under surface conditions found on Europa (Johnson et al., 2012). The phase of the ice on Europa is predominantly determined by crystallization and amorphization effects, which depend in turn on temperature and the deposited dose by charged particles (Mitchell et al., 2017; Strazzulla et al., 1992). At the higher latitudes (>60°), where surface temperatures are <110 K (Ashkenazy, 2019), the crystallization rate is slow (>10^5 years) (Mitchell et al., 2017), which causes ASW to remain amorphous over longer time scales (Berdis et al., 2020). In contrast, at mid-latitudes, where surface temperatures are higher, free radicals that form by irradiation are more mobile and likely to recombine with the crystalline structure, thus reducing the effectivity of amorphization through irradiation (Strazzulla et al., 1992).

We leveraged these measured wavelength-dependent extinction coefficients of vapor-deposited ice (He et al., 2022) to compute the attenuation of solar UV radiation that penetrates near-surface ice of similar characteristics. For each location on Europa's surface, the initial extinction coefficient profile for the near-surface ice column was determined by the mean surface temperature at that location (Ashkenazy, 2019). Then we accounted for the change in the extinction coefficient profile caused by diurnal-scale post-depositional heating by interpolating the measured change between the extinction coefficient profile at the deposition temperature (*i.e.*, average diurnal temperature) and the maximal diurnal temperature (He et al., 2022) (see Supplementary Appendix C). Finally, we evolved the extinction coefficient profiles through time, as a function of depth, by considering the temperature- and deposited dose-driven crystallization and amorphization processes (Mitchell et al., 2017; Strazzulla et al., 1992) (see Supplementary Appendix D), and derived photolytic half-lives of aromatic amino acids embedded therein.

Figure 1 shows the derived photolytic half-lives of aromatic amino acids as a function of latitude and depth for the trailing and leading hemispheres. The longest considered half-life time indicates the slowest estimate for the mean turnover rate of Europa's surface ($\sim 10^8$ years; Doggett et al., 2009). The apparent difference between the two hemispheres, particularly around latitude 50°, can be explained by a considerably faster amorphization of ice in those regions at the trailing hemisphere, a process that increases ice opacity (see Supplementary Appendix D). The difference in amorphization rates is driven, in turn, by lens-like bombardment patterns of energetic electrons that differ between the hemispheres. This results in higher dose deposition in the trailing hemisphere, particularly in the mid-latitudes (Nordheim et al., 2018) (see Supplementary Appendix D).

Figure 2 demonstrates the impact of different degradation mechanisms on the relative abundances of amino acids at various locations on Europa. Given the radiolytic constant of 0.034 MGy^{-1}, degradation is most pronounced within the electron bombardment lenses, up to 30° and 60° for the leading and trailing hemispheres, respectively. In regions where electron bombardment is less prevalent, vapor-deposited ice significantly attenuates the penetration of UV photons and reduces photolytic degradation. As a result, in these areas, the degradation of amino acids is predominantly driven by radiolysis by ions (a detailed discussion can be found in Supplementary Appendix A).

3. Estimating Fluorescence Signal

We coupled two degradation mechanisms to estimate the net longevity of aromatic amino acids as a function of their geographic location and depth on Europa. In approaches that utilize laser-induced UV spectroscopy, it is often assumed that ice is transparent (Eshelman et al., 2019), which would enable the laser to penetrate deeply and the fluorescence to propagate to the surface without severe attenuation. This assumption is inadequate for the case of Europa because, in the absence of an atmosphere to filter harmful UV photons (Plainaki et al., 2018), transparent ice would result in the rapid photolytic degradation of amino acids to greater depths and severely limit the effectiveness of this detection methodology.

Extinction of photon fluxes in vapor-deposited ice protects amino acids from photolytic degradation but also attenuates both the laser beam and the induced fluorescence that travels back to the surface (see Supplementary Appendix E). Our findings indicate that such a laser can effectively penetrate the upper-most millimeter of vapor-deposited ice under europan conditions, which establishes this depth as the critical longevity depth scale of amino acids for significant fluorescence signal detection (see Supplementary Appendix E). In comparison with reported detection thresholds of organic compounds buried in at least 2.4 cm of glacial ice

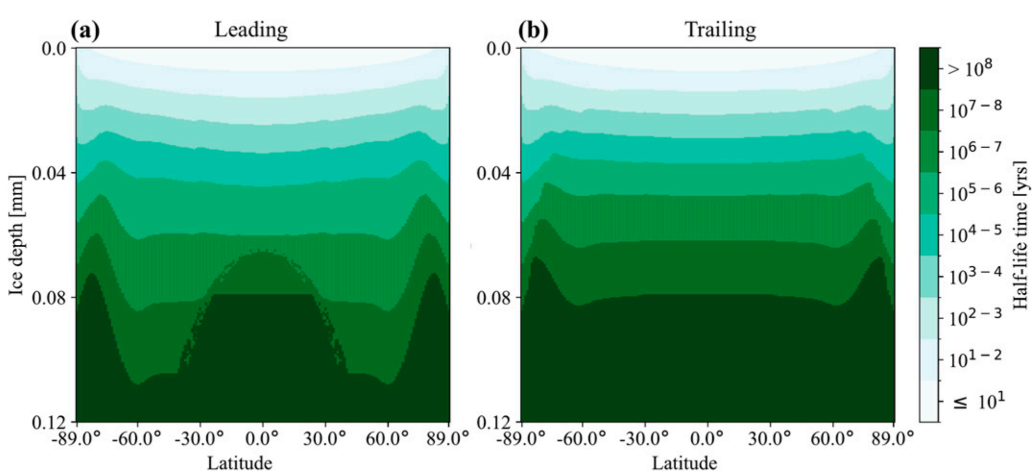

FIG. 1. Photolytic half-lives of aromatic amino acids embedded in thermally evolved vapor-deposited ice that was subject to amorphization and crystallization processes as a function of latitude, depth, and time. (**a**) Leading hemisphere. (**b**) Trailing hemisphere.

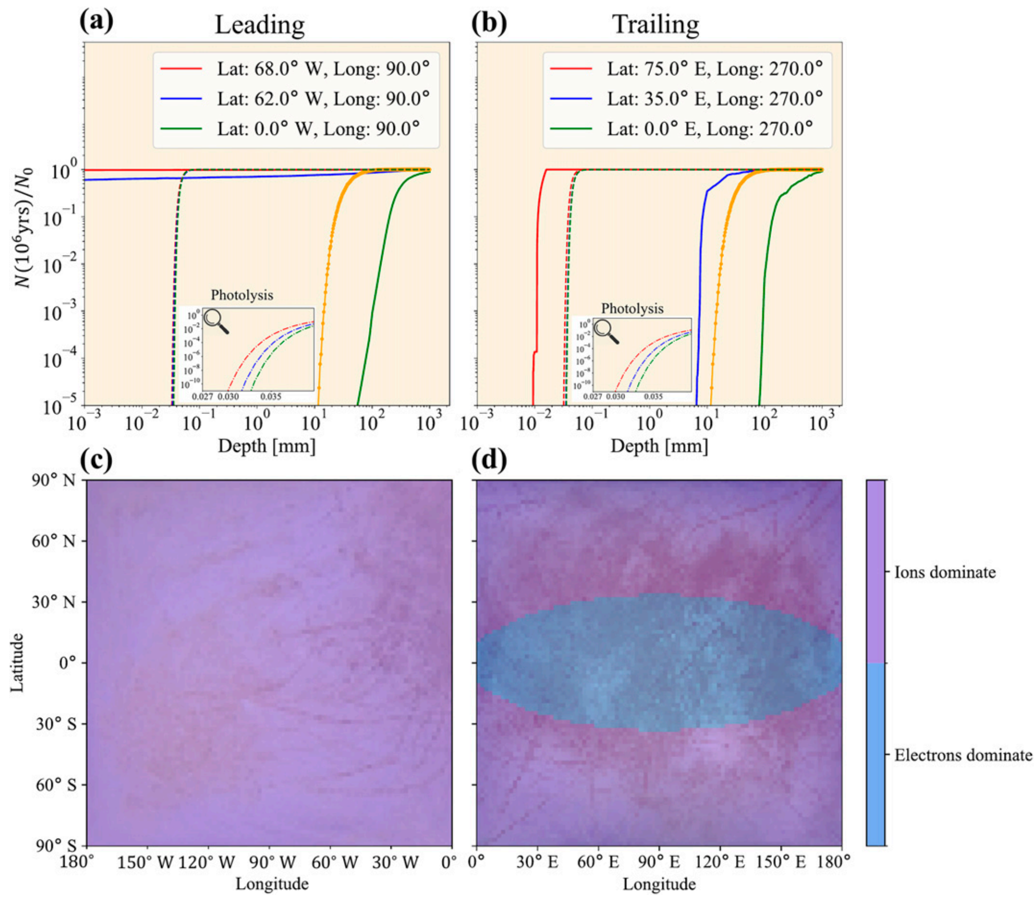

FIG. 2. Effectiveness of distinct degradation mechanisms on Europa, plotted over images of Europa's leading and trailing hemispheres taken by the Galileo spacecraft. **(a)** and **(b)** Relative amino acid concentrations at select locations on the leading and trailing hemispheres, respectively, after being subjected to each distinct and independent degradation mechanism for 10^6 years. Dashed lines: photolysis at select latitudes (colors). Solid lines: radiolysis by electrons at select latitudes (colors). Dotted orange line: radiolysis by ions, which is assumed to be uniform across Europa's surface. **(c)** and **(d)** Most effective degradation mechanism at different locations of the trailing and leading hemispheres, respectively, after 10^6 years, assuming a radiolytic constant of 0.034 MGy^{-1}. Photolysis is not shown as it is not the dominant degradation mechanism anywhere on Europa's surface.

in Earth-like conditions (Eshelman et al., 2019), Europa, and Enceladus to a lesser degree, present more challenging environments for applying such methodology, as the relevant layer prone for detection is also where degradation of organic molecules is fastest.

To assess the detectability of aromatic amino acids through laser-induced spectroscopy, we assumed an initial concentration of tryptophan to be 0.1 ppb and a a mixing ratio of 1:36:66 for tryptophan, tyrosine, and phenylalanine, respectively. The three amino acids were modeled as uniformly-distributed across the vertical ice column. These concentrations represent conservative estimates derived from Earth's oceans (Moura et al., 2013; Yamashita and Tanoue, 2004). Figure 3 illustrates the net number of induced fluorescence photons, as a function of a 248.6 nm laser (Johnson and Hunter, 1980) energy and amino acid concentration, at three nominal terrain ages, which demonstrates the rapid deterioration of the potential signal due to degradation, assuming a radiolytic constant of 0.034 MGy^{-1} (see Supplementary Appendix E). The structure of fluorescence yield, which serves as a proxy for the degradation rate, is primarily controlled by the effectiveness of hemispheric radiolysis lenses, particularly in the trailing hemisphere. Secondary contributions arise from uniformly bombarding ions, with a lesser influence from photolysis, which is further modulated by the ice phase.

It is evident that, given a prohibitive radiolytic constant, even very low concentrations of aromatic amino acids are sufficient to generate a detectable fluorescence signal, potentially even from orbit, given young enough terrain. Polar regions, which are least exposed to solar irradiance and are situated farthest from the electron radiation lenses, present the optimal locations for the detection of aromatic amino acids. Interestingly, the limited evidence of Europa's plume activity points to the south polar region (Roth et al., 2014). If plume activity indeed occurs and is more likely in this region, similar to the case of Enceladus (Yeoh et al., 2015), the convergence of circumstances may create favorable conditions for probing plume ejecta, which would enhance the prospects for detecting aromatic amino acids.

We computed the permissible degradation of the effective upper layer of ice required to produce a statistically significant detection of aromatic amino acid fluorescence across Europa for two plausible detection strategies:

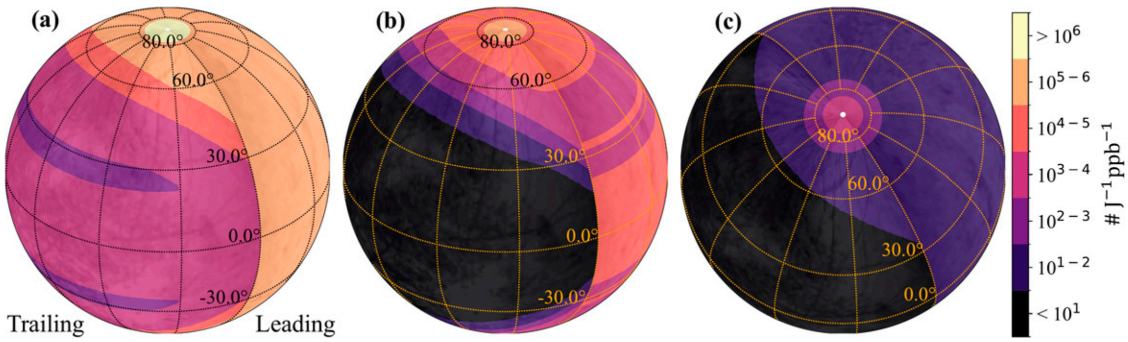

FIG. 3. Net yield of fluorescence photons per unit 248.6 nm laser energy per concentration (ppb) on Europa, given a radiolytic constant of 0.034 MGy^{-1}, at three exposure times to degradation mechanisms: **(a)** 10 years, **(b)** 20 years, and **(c)** 50 years. # denotes the total number of emitted fluorescence photons.

detection by an instrument at the surface or during a close flyby at a 10-km altitude, for the three considered radiolytic constants (a detailed discussion can be found in Supplementary Appendix E). We show that it is feasible to detect a significant fluorescence signal within terrain exposed to Europa's surface conditions for up to several thousand years in the case of a lander mission framework and up to several hundred years in the case of a flyby mission framework, where the polar regions offer the only feasible detection margin for the latter.

4. Conclusion

Our study significantly advances the understanding of Europa's potential to preserve fluorescent biomolecules embedded in near-surface ice despite the harsh conditions on its surface, as well as the ability to detect these molecules. By modeling the effects of radiolysis and photolysis, we have shown that aromatic amino acids, specifically tryptophan, phenylalanine, and tyrosine, can persist within the upper millimeter of ice at high-latitude regions for hundreds of years. This finding is crucial for future astrobiological missions that aim to detect biosignatures on Europa.

The degradation rates of these biomolecules were found to vary significantly with latitude and depth, influenced by the intensity of charged particle bombardment and the phase of the ice. Our results indicate that the leading hemisphere of Europa, sparsely impacted by high-energy electrons, presents a more favorable environment for the preservation of these amino acids compared to the trailing hemisphere, which is exposed to lower-energy particles that are more numerous with shallower penetration depths. This said, the radiolytic constant of aromatic amino acids in the near-surface ice of Europa, which plays a critical role in determining their longevity therein, is poorly constrained. Factors such as ice impurities and the manner in which organics are clumped in the ice introduce variability that necessitates further study.

We have shown that laser-induced fluorescence spectroscopy can effectively detect these biomolecules even from orbit. This technique can penetrate the upper-most millimeter of vapor-deposited ice, making it attractive for potential future missions that may target geologically young terrain, such as plume ejecta. Specifically, our findings underscore the importance of the polar regions on Europa as prime targets for potential biosignature detection, where organic compounds in detectable concentrations may be preserved. Future missions equipped with spectroscopic instruments will be well positioned to explore these regions and potentially uncover evidence of biotic or abiotic synthesis of complex biomolecules. The ability to predict the presence of fluorescent organic molecules other than aromatic amino acids on Europa's surface is critical for evaluating the feasibility of UV-induced fluorescence detection approach potential of aromatic amino acids. Detecting these coexisting molecules can, on the one hand, attenuate the unique fluorescence signatures of the aromatic amino acids and, on the other, (without hand), provide additional context, revealing interactions between various organics and Europa's radiation-altered ice. Such insights could help elucidate the history and origin of the extant organic material on Europa's surface.

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Supplementary Material

Supplementary Appendix A
Supplementary Appendix B
Supplementary Appendix C
Supplementary Appendix D
Supplementary Appendix E
Supplementary Appendix Table E1
Supplementary Appendix Table E2

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Abbreviations Used

ASW = Amorphous Solid Water
DUV = Deep Ultraviolet
G4beamline = GEANT4-Based Simulation Toolkit for Beamline Modeling
GEANT4 = Geometry and Tracking (version 4) – Simulation Toolkit
MA = Molecular Assembly (Index)
MGy = Megagray (10^6 Gray, unit of absorbed radiation dose)
MIR = Mid-Infrared
NIR = Near-Infrared
PAHs = Polycyclic Aromatic Hydrocarbons
ppb = Parts Per Billion
SNR = Signal-to-Noise Ratio
UV = Ultraviolet