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Impacts on Ocean Worlds Are Sufficiently Frequent and Energetic to Be of Astrobiological Importance

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Abstract

Evidence for the beneficial role of impacts in the creation of urable or habitable environments on Earth prompts the question of whether meteorite impacts could play a similar role at other potentially urable/habitable worlds like Enceladus, Europa, and Titan. In this work, we demonstrate that to first order, impact conditions on these worlds are likely to have been consistent with the survival of organic compounds and/or sufficient for promoting synthesis in impact melt. We also calculate melt production and freezing times for crater sizes found at Enceladus, Europa, and Titan and find that even the smallest craters at these worlds offer the potential to study the evolution of chemical pathways within impact melt. These first-order calculations point to a critical need to investigate these processes at higher fidelity with lab experiments, sophisticated thermodynamic and chemical modeling, and, eventually, in situ investigations by missions.

Unified Astronomy Thesaurus concepts: Titan (2186); Enceladus (2280); Europa (2189); Impact phenomena (779); Craters (2282)

1. Introduction

Though perhaps more commonly thought of as an annihilating force (e.g., Maher & Stevenson 1988; Sleep et al. 1989), impact events may have supported the emergence of life on Earth, as recently summarized by Osinski et al. (2020). Over the course of Earth's history, but especially during the Hadean when the impact rate was orders of magnitude higher than the modern flux (Chyba 2000; Ferus et al. 2021), impact events have delivered volatiles and organics, generated new substrates and compounds, and created a variety of environments advantageous to the emergence (urable; Deamer et al. 2022) or sustainment (habitable) of life on Earth.

For example, during a typical impact cratering event on Earth, much of the impactor melts and some of it vaporizes but volatiles and bioessential materials like organics (including amino acids) are not necessarily lost or even destroyed, depending on the impact conditions (e.g., Pierazzo & Chyba 1999; Blank et al. 2001; Pierazzo & Chyba 2002; Parnell et al. 2010). Exogenously delivered materials have been estimated to be an important source of organics on early Earth (Chyba & Sagan 1992; Maurette 1998). Shockwaves could provide the energy for organic synthesis of important precursors like HCN (Mukhin et al. 1989; Cockell & Bland 2005) or amino acids (Martins et al. 2013). The iron and heat from very large impactors can facilitate the reducing atmospheric conditions necessary for abundant HCN production (Wogan et al. 2023). Impacts fracture and, in typical terrestrial events, melt the target: the more permeable substrates and excavation of deeper rock layers promote hydrothermal activity (e.g., Osinski et al. 2013) and endolithic habitats (e.g., Cockell & Bland 2005).

Could impacts play a similarly constructive role in the habitability or urability of niche environments on the Ocean Worlds of the outer solar system? While the subsurface oceans represent tantalizing astrobiological targets due to the availability of liquid water, major questions remain about the availability of other key factors for habitability or the emergence of life: are chemical ingredients and energy sources sufficiently abundant and collocated? Over sufficient timescales? With sufficient cycling? (Defining "sufficient" for any of these factors is of course its own separate realm of investigation that can be informed by characterizing the extraterrestrial environments in concert with the effort of evaluating whether they are inhabited, were inhabited, or could be inhabited; e.g., Méndez et al. 2021; Barge et al. 2022). Impact processes are likely an important part of the answers to these questions, as impacts can drive exchange through the ice crust—either through direct seeding (e.g., Pierazzo & Chyba 1999; Crósta et al. 2021; Neish et al. 2024) or flushing through the crust (Carnahan et al. 2022; Kalousová et al. 2024)

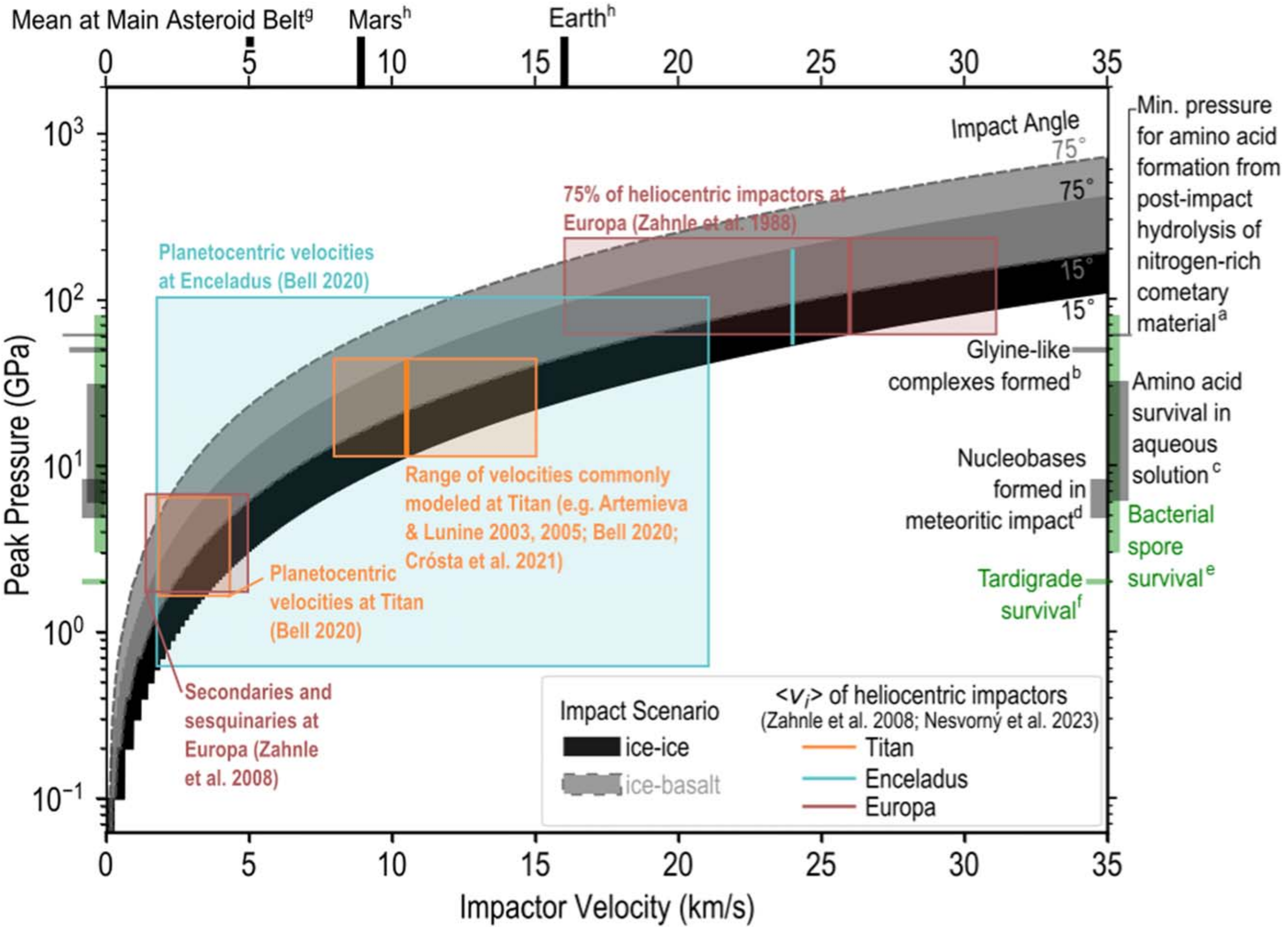

Figure 1. Impact velocities and first contact pressures relevant to OW for ice (solid, black) and basalt (dashed, gray) projectiles into ice targets at a representative span of impact angles between 15° and 75°. Shock studies of biota (green) or biologically relevant molecules (black) shown along the *y*-axes; impactors in the inner solar system shown at the top for context. Vertical orange, teal, and magenta bars indicate the average impact velocity of heliocentric impactors calculated by Zahnle et al. (2008); Nesvorný et al. (2023)[a]; Martins et al. (2013)[b]; Goldman et al. (2010)[c]; Blank et al. (2001)[d]; Furukawa et al. (2015)[e]; Horneck et al. (2001); Burchell (2007); Stöffler et al. (2007); Burchell et al. (2014)[f]; Traspas & Burchell 2021[g]; O'Brien & Sykes (2011)[h]; Le Feuvre & Wieczorek (2008).

—and therefore drive episodic influxes of organic and inorganic materials from the surface and/or from the impactor itself. Impacts can also generate ephemeral microcosms: any liquid water melted during impact freezes out over timescales commensurate with the impact energy (e.g., Pierazzo & Melosh 2000; Artemieva & Lunine 2003; Barr & Citron 2011; Kalousová et al. 2024). The exciting potential for chemistry within these pockets has been established, from concentrating salts (Steinbrügge et al. 2020) to driving amino acid synthesis (e.g., Thompson & Sagan 1992; Neish et al. 2008, 2010). Furthermore, shock-driven chemistry of icy, sometimes organic-rich (in the case of Titan especially) target materials may generate new "seed" compounds (e.g., amino acids or nucleotides) in the melt pool (e.g., Pearce et al. 2024).

Can and do impact events significantly contribute to surface and shallow subsurface chemistry on Ocean Worlds? How do impact velocities and impactor compositions affect the survivability of organics or even microbes? In this work, we show that to first order, the temperatures, pressures, and timescales of impacts at the Ocean Worlds motivate the hypothesis that impacts could be beneficial for at least prebiotic chemistry at Ocean Worlds. Different aspects of impacts may be more important to habitability or urability at some Ocean Worlds compared to others, especially given the diversity of surface compositions and expected impactor velocities at different Ocean Worlds. Much work remains to evaluate this hypothesis, but our results point to the increasing importance of and need for the higher-fidelity laboratory and theoretical studies.

2. Methods

2.1. Relevant Initial Shocks

To investigate the initial shock levels of the ice-on-ice impacts expected to be the most common for the Ocean Worlds (i.e., "cometary" impactors, presumably originating from the Kuiper Belt and Oort cloud), we used the planar impact approximation (Gault & Heitowit 1963; Melosh 2012) to relate impactor velocity to the maximum pressure achieved by the impact (Figure 1). In this approximation, the Hugoniot equations defining the conservation of mass, energy, and momentum can be solved for peak pressure by assuming a linear relationship between the shock velocity and particle velocity. We use the linear shock wave equation of state (EOS) for water ice from Stewart & Ahrens (2005). We ran the same calculations assuming a stony projectile with the EOS for basalt given in Ahrens & Johnson (1995). In both cases, these particular EOSs are linear EOSs that do not include phase transitions. Robust three-dimensional numerical impact models that used more sophisticated EOSs would lead to more accurate

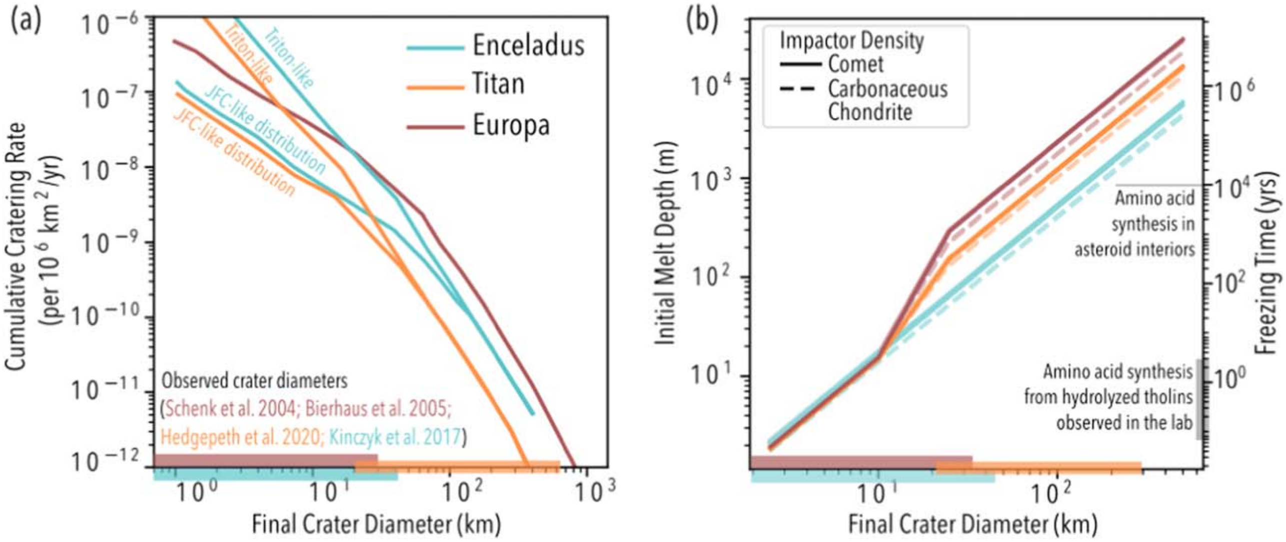

Figure 2. (a) Cumulative cratering rates assuming heliocentric, cometary impactors from Zahnle et al. (2003). Observed crater diameter ranges from the distribution of observed craters on Europa, Titan, and Enceladus. (b) Initial depth of melt and freezing timescales calculated as in Kraus et al. (2011) for impactors of differing densities.

values for the maximum pressure achieved by the impact by treating phase transitions more accurately, thus allowing a better characterization of the decrease in shock pressure with distance from the impact point in the numerical modeling. The simplified, one-dimensional approach used here gives a first-order sense of how these maximum pressures vary between Ocean Worlds, which is sufficient for the goals of this work.

Relevant impactor velocity ranges are taken from the literature for different populations of impactors. For the Jupiter system, the observational constraints on the abundance of ecliptic comets suggest that these represent the bulk of impactors in the system (Zahnle et al. 2003). These impactors travel along heliocentric orbits and thus tend to arrive at high velocities; Monte Carlo simulations yield an average impact velocity of $<v_i> = 24–26\,\mathrm{km\,s^{-1}}$ for the ∼1 km diameter comets that yield 20 km craters in ice (Zahnle et al. 2003; Wong et al. 2021). However, when considering the astrobiological implications of impacts, we argue that the secondaries and sesquinaries known to facilitate material exchange—be it icier materials from Europa itself or Ganymede or rockier materials from Io—should also be considered. Secondaries are impacts created by the ejecta of a larger impact while sesquinaries are secondaries that are sufficiently energetic to escape the primary body and impact another. Secondaries and sesquinaries arrive with less kinetic energy and therefore are less likely to produce large volumes of melt (escape velocities of Io, Europa, and Ganymede are 2.3, 1.9, and 2.6 $\mathrm{km\,s^{-1}}$) but are more frequent than primary impacts (Zahnle et al. 2008).

The cratering history of the Saturnian system is less well understood. The cratering records of the mid-sized satellites hint at a unique planetocentric population of unknown composition (Kirchoff et al. 2018; Ferguson et al. 2022). These impactors in orbit around Saturn would also arrive at lower average velocities than the heliocentric populations—with impact velocities ranging from tens of $\mathrm{m\,s^{-1}}$—tens of $\mathrm{km\,s^{-1}}$ for Enceladus and a few $\mathrm{km\,s^{-1}}$ for Titan—but may dominate cratering events (Bell 2020). Low-velocity secondaries may also be important: Bottke et al. (2024) suggest that the cratered plains of Enceladus are the result of impacts by debris from a surface resetting, a much larger impact. Average impacting velocities for heliocentric impactors are much higher at Enceladus (closer to Saturn) than Titan.

2.2. *Melt Production and Timescales*

The cumulative cratering rates at Titan, Enceladus, and Europa as predicted by the dynamical modeling of Zahnle et al. (2003) are shown in Figure 2(a), along with the ranges of observed crater sizes (Schenk et al. 2004; Bierhaus et al. 2005; Kinczyk et al. 2017; Hedgepeth et al. 2020). Informed by these final crater sizes, we determined melt production volume via the formulation of Kraus et al. (2011) for a set of final crater diameters (D_f) spanning the observed and predicted values: 2.5, 5, 10, 25, 50, 125, and 500 km. First, we solved for the transient crater radius (Kraus et al. 2011, their Equation (33)). This includes taking into account the transition from simple to complex craters specific to each world (from Zahnle et al. 2003) and selecting the composition of the impactor. Impactors are modeled as comet-like (density, $\rho_i = 500\,\mathrm{kg\,m^{-3}}$; porosity, ϕ_i, of 0.75) for heliocentric impactors and carbonaceous chondrite-like for planetocentric impactors ($\rho_i = 2500\,\mathrm{kg\,m^{-3}}$; $\phi_i = 0.3$). The radius of the impactor (R_i) is then determined from the π-scaling relationship for water ice (Kraus et al. 2011, their Equation (32)). We assume a spherical impactor to determine the total mass and multiply this value by the mass fraction (relative to the impactor) of melt and vapor produced during impact (ζ) (Kraus et al. 2011, their Equation (12)), which is a function of target surface temperature (T), impactor velocity (U), impact angle (θ), and the melt number (U^2/E_M):

$$M_{\mathrm{Melt+Vapor}} = \frac{4\pi}{3} R_i^3 \rho_i \zeta(T,\, \theta,\, \phi_i,\, U^2/E_M). \quad (1)$$

The fraction of melt left in the crater (f) is expected to vary by tens of percent with the impactor velocity based on the modeling of Kraus et al. (2011) who derived a scaling relationship to the transient crater size (their Equation (28)). We estimate the maximum initial melt depth of a flat melt sheet occupying one-sixth of the final crater diameter following

Artemieva & Lunine (2005):

$$h = \frac{170}{\pi}\frac{fM_{\text{Melt+Vapor}}}{\rho_m D_f}. \qquad (2)$$

Freezing timescales are also calculated as per Artemieva & Lunine (2005) and Thompson & Sagan (1992), using the latent heat of fusion for water ice ($E_M = 3.3 \times 10^5\ \text{J kg}^{-1}$)

$$t_{\text{freezing}} = \frac{\rho_m E_M h^2}{k(\Delta T)}, \qquad (3)$$

where ρ_m is the density of the melt (assumed to be $1000\ \text{kg m}^{-3}$), k is the thermal conductivity of water ice ($2.2\ \text{W m}^{-1}\ \text{K}^{-1}$), and ΔT is the temperature difference between the freezing point (273 K) and the surface temperature of the moon.

3. Results

3.1. Initial Shock Conditions

At first contact, impactor material and the top layer of the ice crust are subject to shock pressures >1 GPa (Figure 1) for the expected impactor velocities at Enceladus (cyan), Europa (maroon), and Titan (orange). Rocky (dashed) impactors create higher contact pressures than ice (solid) and higher impact angles (measured with respect to surface tangent) increase the contact pressure (grayscale lines). It is important to note that only a small fraction of the target area is subject to these peak pressures.

The peak pressures at impact can be compared to astrobiologically relevant thresholds identified in the literature for the survivability of compounds important to prebiotic chemistry and even living matter. Generally, survival rates of bioessential elements, organic molecules, and even biota are nonzero across relevant pressures (see ranges at the right of Figure 1) but do decrease with increasing pressure. Peterson et al. (1997), for example, showed that amino acid decomposition and racemization decreased by a factor of 1000 from 5 to 30 GPa. The majority of heliocentric impactors at Europa and Enceladus experience greater peak pressures than the range of pressures at which bacterial spores have been demonstrated to survive (Horneck et al. 2001; Burchell 2007; Stöffler et al. 2007; Burchell et al. 2014). However, the abundance of material that survives is likely nonnegligible: peak pressures and temperatures are only experienced by a fraction of the impactor's leading hemisphere (Schultz & Gault 1990; Pierazzo & Melosh 2000; Potter & Collins 2013). Furthermore, higher first-contact pressures may facilitate the synthesis of compounds in post-impact hydrolysis (Martins et al. 2013).

Titan's average heliocentric impactors have lower impact velocities, creating peak pressures that fall in the ranges of both bacterial spore survival and amino acid survival/formation observed in the lab. The wide range of planetocentric impactor velocities at Enceladus also spans these pressures. Conditions for the retention of impactor organics and the creation of new compounds are perhaps most favorable in these impact scenarios.

3.2. Melt Production and Timescales

The cumulative cratering rates predicted by Zahnle et al. (2003) are compared to those observed at Europa (maroon bar, *x*-axis; Schenk et al. 2004; Bierhaus et al. 2005), Enceladus (cyan; Kinczyk et al. 2017), and Titan (orange; Hedgepeth et al. 2022) in Figure 2(a). Both the observed and hypothesized cumulative populations are important to consider for these three worlds, as resurfacing by the geological processes can easily remove smaller features that, though they likely produce small volumes of melt that will freeze quickly, may still host interesting chemistry given the timescales of reactions observed in the lab. The surfaces of Europa, Enceladus, and Titan are relatively young, with few observed craters (with the exception of portions of Enceladus that are heavily cratered; Kirchoff & Schenk 2009; Kinczyk et al. 2024) due to resurfacing and/or erosion. Thus, the observed crater count is a lower limit on the total occurrence of impacts and a lower limit on the total astrobiological potential of impacts. After all, resurfacing processes may obscure past events but, in doing so, they redistribute impact-generated products.

Amino acids have been synthesized in terrestrial labs from hydrolyzed Titan haze analogs ("tholins") over much shorter timescales (months–years; Neish et al. 2008, 2010), suggesting that interesting chemistry may take place even in small impact events on Europa and Enceladus, assuming the necessary ingredients are present in the ice crust and/or the impactor since survivability of impactor material will be higher at the lower shock conditions of small impacts (Figure 1). For the observed craters on Enceladus and Europa, the longest-lived melts last only a few hundred years; on Titan, time to completely freeze the melt pools of observed craters may be 100s–10,000s yr (Artemieva & Lunine 2003, 2005; O'Brien et al. 2005; Hedgepeth et al. 2022; Wakita et al. 2022, 2023; Kalousová et al. 2024). The higher impactor velocities expected at Europa could drive higher melt production than at Titan. Few craters of such sizes are evident on Europa's surface today, but these observed craters are a lower bound because much of Europa's impact history has been erased by ice shell processes. Bottke et al. (2024), for example, propose a new crater scaling law for Europa and Titan based on observations of Ganymede that imply older surfaces and more frequent global resurfacing events than if the scaling law is tied to the crater distributions of smaller satellites.

Final craters <tens of kilometers in diameter are more common both in the observed craters and modeled impact rates at Enceladus and Europa. These small melt volumes (if produced at all) may still be liquid long enough for amino acid synthesis, based on laboratory reaction rates (Neish et al. 2008, 2010), assuming that organic material survives impact or is already available in the target substrate (perhaps emplaced by plume fallout, for example, at Enceladus' south pole). In general, but especially at these smaller final crater diameters on Enceladus and Europa, melt production (and thus freezing timescales) is minimally affected by the density and porosity of the impactor (Figure 2(b)).

Assigning impactor velocity based on final crater size, we can associate each observed crater on Enceladus (Kinczyk et al. 2017) and Titan (Hedgepeth et al. 2020) (where such preliminary and published catalogs have been created) with a possible melt production volume and freezing time. Grouping by crater size, we show the total melt production in Figure 3. Enceladus is highly sensitive to impactor velocities: if most impactors are heliocentric comets, almost 200 km^3 of melt could have been produced in just the observed craters. Melt, if created in the smallest craters ($\leqslant$4 km diameter), freezes on the order of just a few Earth years, but with hundreds of craters of

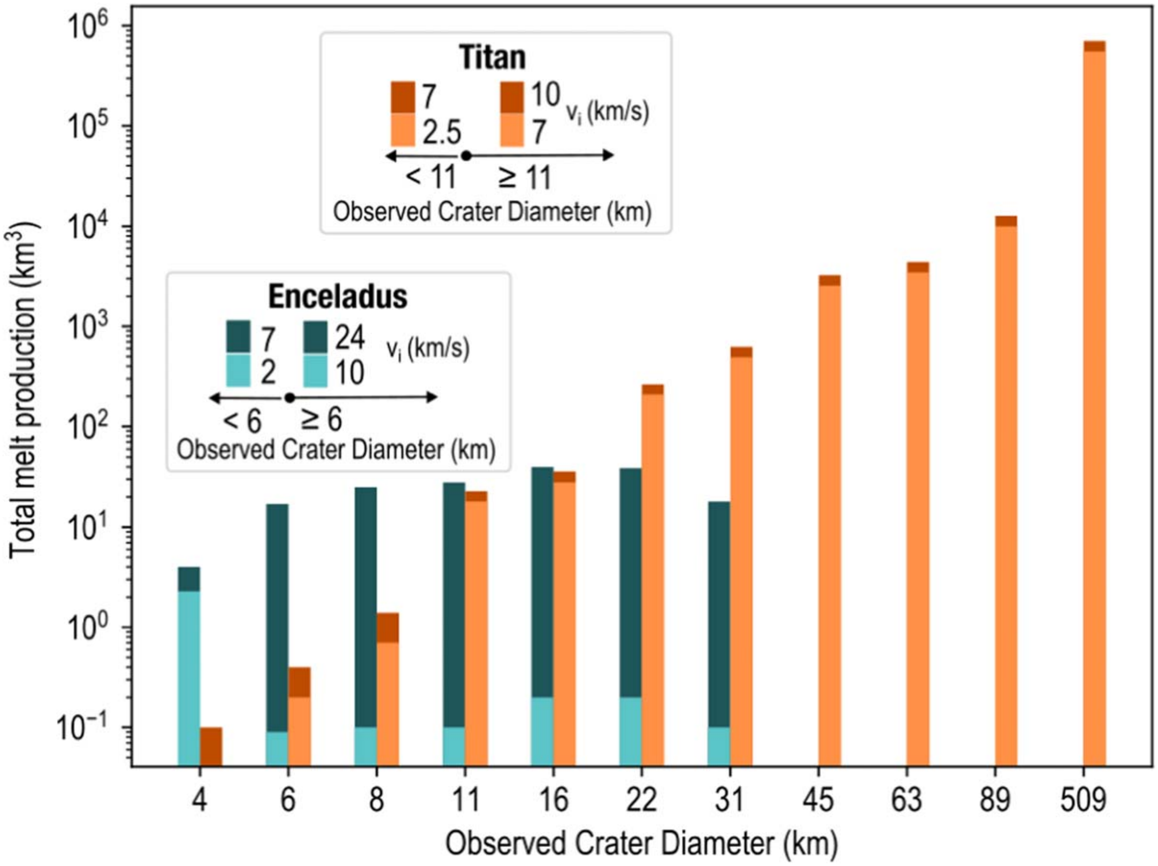

Figure 3. Total melt production for observed craters on Enceladus (cyan) and Titan (orange), binned by observed crater diameter. Impactor velocities (v_i) were assigned to span expected values at each body (i.e., the width of boxes in Figure 1) based on the crater diameter bin; darker colors represent the maximum velocity while lighter colors represent the minimum. (The necessary catalogs of impact craters do not yet exist to conduct this analysis for Europa.).

this size found on Enceladus (Kirchoff & Schenk 2009; Kinczyk et al. 2017), this is a significant number of "experiments" in which to evaluate what chemical pathways may have taken place.

At Titan, the retarding and screening effects of the atmosphere mute the range of possible impact velocities and final crater sizes. Regardless of impactor population, the total melt production is on the order of ∼600,000 km^3. Titan's total crater population, though smaller than Europa or Enceladus, offers the opportunity to evaluate chemical pathway evolution in conditions where the melt volume, availability of organics, and time are more abundant than other moons.

4. Discussion

Historically, interest in the astrobiological potential of impacts at Ocean Worlds has mostly centered around whether impactors can deliver new materials to the body for eventual transport through the crust to the subsurface oceans. Pierazzo & Chyba (2002), for example, showed that the survivability of amino acids varies both on the composition of the amino acid and the impactor velocity. Integrating over Europa's history, these rates are insufficient to seed the subsurface ocean to terrestrial amino acid concentrations, even assuming 100% efficient transport. The authors thus concluded that cometary delivery was unlikely to be a driving source of complex organics for Europa's ocean.

Here, however, we offer a different lens through which to evaluate the significance of material delivery by focusing on the localized liquid environment of each instance of impact melt. If we apply the Pierazzo & Chyba (2002) results to just the crater melt pool, the chemical potential is much greater: a 15 km diameter crater formed by a comet traveling at the average impactor velocity at Europa produces ∼1 km^3 of melt (Figure 2(b)). If the cometary abundance of glycine is that of 67P (Hadraoui et al. 2019), then Pierazzo & Chyba's (2002) retention and survival rates give ∼parts per million concentrations of glycine in the melt, 3 orders of magnitude higher than production by heating at hydrothermal vents (Cleaves et al. 2009; Sugahara & Mimura 2015). Thus, impactors seed whatever chemistry happens in the melt, providing organic and other essential elements depending on the impactor composition.

Figure 1 supports the hypothesis that some impact events at Europa, and likely more at Enceladus and Titan, arrive with sufficiently low energies to either allow the survival of organics carried by the impactor or facilitate reactions. At Europa and Enceladus, the survival and deposition of impactor organics is more important as there are fewer surface organics within the ice crust to seed the melt pool. On Titan, the survival of elements like phosphorous may be more important (Pasek et al. 2011). Thus, even the small, more frequent impact events (probably more representative of the sesquinary/secondary/planetocentric impactor populations) contribute to the astrobiological potential by delivering less modified compounds to the surface that are available either for immediate reaction if melt is produced or for future processing (including in subsequent impact events).

In addition to the composition of the impactor, the extent and duration of the impact melt will drive the possible chemical pathways. In our simple model (Equation (3)), freezing times scale with depth. Convolving a simple melt production model with the observed distribution of craters on Enceladus, Europa, and Titan supports the hypothesis that the melts produced over the history of these bodies have been frequent and long-lived enough to be of astrobiological interest. With the preliminary and published crater catalogs of Enceladus (Kinczyk et al. 2017) and Titan (Hedgepeth et al. 2020), we can predict how many of these would have melt lasting longer than 1 Earth year (an arbitrary threshold for "interesting" chemistry based on the timescales of tholin hydrolysis in the lab; more work to elucidate what thresholds are relevant for each world is needed). For Enceladus, ∼270 craters meet this threshold if created by a heliocentric, cometary impactor; ∼90 if created by a planetocentric, cometary impactor. Of course, these specific numbers are imprecise given the key unknowns surrounding our understanding of the impactor populations, as well as impact melt generation and evolution. But, these calculations suggest that there may have been at least hundreds of melt pool "laboratories" even on tiny Enceladus. On Titan, heliocentric and planetocentric cometary impactors yield melt freeze times above this threshold for ∼110 and ∼90 craters, respectively. Each "laboratory" may not represent a currently habitable or urable environment but would certainly provide powerful insight into prebiotic chemical pathways, thus helping build the spectrum of abiotic chemistry necessary for more nuanced classifications at each world for where the "biological chemistry" threshold lies (e.g., as advocated by Barge et al. 2022).

These first-order results are based on 1D approximations and limited laboratory data, however. Higher fidelity modeling of freezing and melt production is needed to fully explore the environmental conditions expected within the melt. For example, calculating melt freezing times with an analytical solution to the Stefan problem yields ∼60% of the results of Equation (3). Furthermore, impurities in the melt concentrate as the water freezes, which can decrease the freezing point of the melt itself as well as lowering the melting temperature of surrounding impurity-laden ice (Chivers et al. 2021; Hedgepeth et al. 2022; Buffo et al. 2023). Cryoconcentration of impurities amplifies the concentration of biologically relevant species (like HCN) and can improve reaction rates (e.g., Hedgepeth et al. 2022). Finally, forward modeling of melt production can more accurately predict the volume and, importantly, distribution of melt within a crater than the model and assumptions we make here. These studies are computationally intensive and do not yet span the full range of impact scenarios at Ocean Worlds. Wakita et al. (2022), for example, conducted a detailed study of ∼80 km diameter craters to investigate the implications for Dragonfly's exploration of Selk Crater. They found that while total melt volume was independent of the extent of a clathrate layer in the crust, the distribution of melt (and thus the freezing timescale) is sensitive. Cox & Bauer (2015) conducted a broader modeling campaign for Europa craters but focused on the likelihood of breaching rather than melt production. Carnahan et al. (2022) used these results to investigate the evolution of melt chambers that do not directly breach and showed the conditions under which melt may drain into the subsurface ocean.

The survivability of rockier compounds in ice impacts is relatively unstudied, but these elements are likely to play a key role in parameters like pH and salinity, which affect both the thermodynamics and chemistry possible in the melt (e.g., Brassé et al. 2017). Here we treat composition very broadly, whereas real impactors and targets will be mixtures. Pure ice, for example, may not be a suitable target composition for Titan; the presence of methane clathrates is anticipated and will affect the production of melt (Wakita et al. 2022; Kalousová et al. 2024).

Of course to take full advantage of the range of natural experiments that have played out across the surfaces of Enceladus, Europa, and Titan, in situ sampling of the impact materials is required. Dragonfly, NASA's fourth New Frontiers mission, is designed to do so at Titan (Barnes et al. 2021), providing the first ground truth for the hypothesis that impacts have played an astrobiologically important role in the evolution of chemistry at Ocean Worlds. The measurements made by the Dragonfly Mass Spectrometer (DraMS) will revolutionize our understanding of Titan's surface chemistry. DraMS data are specifically designed to enable the identification of organic compounds relevant to prebiotic chemistry (like amino acids; Barnes et al. 2021; Grubisic et al. 2021; Moulay et al. 2023). Thus, by comparing the composition of organics that have not interacted with liquid water (such as the sands that make up the equatorial dunes, Dragonfly's first target landing site; Lorenz et al. 2021) with organics that have hydrolyzed in previously melted environments like the now-frozen impact melt, expected near the Selk crater (Neish et al. 2018), we can piece together the chemistry that unfolded post-impact. Complementing this deep dive into the organic chemistry will be data from the Dragonfly Gamma Ray and Neutron Spectrometer (DraGNS; Lawrence et al. 2022). The bulk elemental abundances derived from DraGNS spectra taken at each landing site will reveal whether key elements like potassium, sulfur, and phosphorous are present. If these elements are only found in impact-related terrains, this may point to an exogenic origin, especially since the impact at Selk was likely too small to have punched through Titan's thick ice crust (Zahnle et al. 2014; Kalousová et al. 2024; Neish et al. 2024). Determining if and how these elements are incorporated in hydrolyzed products will be an important part of piecing together the chemical pathways enabled by Titan's transient liquid environments, and, therefore, their role in prebiotic chemistry at Titan and other Ocean Worlds.

5. Conclusion

We show that impact conditions at Enceladus, Europa, and Titan create environments relevant to prebiotic chemistry and, thus, have astrobiological implications. Each impact event's impact velocity, impactor size, impactor composition, and ice target composition creates an experiment in which chemical pathways relevant to prebiotic chemistry may be taking (or have taken) place. Even the small, more frequent impacts that produce little melt offer the opportunity to investigate shorter-lived hydrolysis. Alternatively, lower velocities that frustrate melt production enable the survivability of impactor material, thereby seeding the surface with exogenic material. Deeper dives into the physics and chemistry of impacts, specifically at Ocean Worlds, are needed to fully explore how these ubiquitous events have influenced astrobiological potential in the outer solar system.

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