

Is extraterrestrial life suppressed on subsurface ocean worlds due to the paucity of bioessential elements?

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ABSTRACT

The availability of bioessential elements for “life as we know it”, such as phosphorus (P) or possibly molybdenum (Mo), is expected to restrict the biological productivity of extraterrestrial biospheres. Here, we focus on worlds with subsurface oceans and model the sources and sinks of bioessential elements. We find that the sinks of P are likely to dominate over its sources provided that these oceans are either neutral or alkaline and possess hydrothermal activity. Hence, we conclude that the P in subsurface oceans could be depleted over Myr timescales, thereby leading to oligotrophic or non-existent global biospheres and low chances of life being detected. Along these lines, any potential biospheres in the clouds of Venus may be limited by the availability of Mo. We also point out the possibility that stellar spectroscopy can be used to place potential constraints on the availability of bioessential elements on planets and moons.

1. INTRODUCTION

Most studies of habitability, especially from an observational standpoint, rely upon a “follow the water” strategy (Cockell et al. 2016). Whilst this pragmatic approach offers simplicity, it is also inherently incomplete since water is only one of the many conditions that are necessary for the chemistry of “life as we know it”. As a result, some studies have advocated the adoption of the “follow the energy” approach as a more comprehensive alternative (Hoehler et al. 2007). Clearly, the availability of energy sources will limit the maximum biomass that can be supported within a given ecosystem. As a result, several studies have sought to quantify the biological potential of habitable worlds by assessing the available energy sources and extrapolating from terrestrial ecosystems (Chyba & Hand 2001; Marion et al. 2003).

Although the study of available free energy sources is indubitably important, there is one other factor that has not been sufficiently explored: the availability of nutrients. Even when a particular planet (or moon) possesses plentiful free energy, if bioessential elements like phosphorus, nitrogen, molybdenum and iron are present in very low concentrations, they will set limits on the biological potential of that world (Lingam & Loeb 2018). In this paper, we focus on this aspect and study the availability of such elements on worlds with subsurface oceans. Our choice for the latter is dictated by the fact that these worlds are common in our Solar system

(Lunine 2017) - most notably Europa and Enceladus - and there are many missions that are either in development, for e.g. Europa Clipper,¹ or under review. In addition, several recent observational breakthroughs have revealed that these worlds possess many of the requisite ingredients for being habitable (Nimmo & Pappalardo 2016; Waite et al. 2017; Sparks et al. 2017).

2. OCEAN WORLDS AND NUTRIENTS

We start by describing how ocean productivity is governed by the availability of limiting nutrients such as phosphorus and nitrogen on Earth.

2.1. Limitations on ocean productivity

There has been a great deal of debate as to what constitutes the limiting nutrient (LN) insofar the total ocean productivity is concerned. This is not an easy question to answer since nutrient limitation can be manifested in different ways, and across varied timescales. The scarcity of nutrients can affect the growth rates of individual cells and the theoretical upper bound on the biomass, corresponding to the Blackman and Liebig limitations. In recent times, the significance of nutrient co-limitation has also been emphasized, wherein two or more elements limit ocean productivity. Moreover, different elements may serve as the limiting factors depending on the timescales under consideration - this prompted Tyrrell (1999) to distinguish between the proximate and ultimate limiting nutrients, with the latter governing ocean productivity over long timescales.

¹ <https://www.jpl.nasa.gov/missions/europa-clipper/>

On Earth, the net primary productivity (NPP) is proportional to the availability of nutrients via the factor γ that quantifies the effect of nutrient availability on the maximum growth rate (Sarmiento & Gruber 2006). It is common to model γ using the Monod equation:

$$\gamma = \frac{[N]}{\mathcal{K} + [N]}, \quad (1)$$

where $[N]$ is the concentration of the limiting nutrient and \mathcal{K} is the corresponding Monod constant. This function is well-justified on observational grounds, as seen from Figure 4.2.6 of Sarmiento & Gruber (2006). An immediate consequence of the above discussion is that $\text{NPP} \rightarrow 0$ when $[N] \rightarrow 0$ in the context of this simple model. Hence, in this limit, any biospheres (if present) may be highly oligotrophic, and would therefore have a relatively low likelihood of being detectable.

2.2. Which element limits total productivity?

Bearing in mind the complexity of nutrient limitation, the three most prominent candidates for the limiting element are nitrogen (N), phosphorus (P) and iron (Fe). Traditionally, P (in the form of phosphates) has been considered to be the limiting element by geochemists whereas N (in the form of nitrates) has been regarded as the limiter by biologists. Support for N comes from the fact that nitrate is depleted slightly prior to phosphate, and the addition of nitrate stimulates growth in many nutrient-limited environments while the addition of phosphate does not produce an equivalent effect.

Those who argue in favor of P as the limiting element have pointed to the absence of nitrogen fixation and denitrification analogues for phosphates. Hence, the availability of P is wholly contingent on its delivery from external sources, and has been argued to be the ultimate limiting nutrient defined earlier (Tyrrell 1999). On Earth, recent evidence suggests that the rise in oxygen levels and the diversification of animals coincided with a fundamental shift in the phosphorus cycle in the late Proterozoic era around 800 to 635 Ma (Reinhard et al. 2017; Cox et al. 2018). Prior to this period, there is widespread evidence indicating that the availability of P was much lower than today, consequently suppressing primary productivity (Kipp & Stüeken 2017). If the emergence of animals was indeed linked with the P cycle, the availability of nutrients (especially phosphorus) could be directly tied to animal evolution on Earth (Knoll 2017), as well as on other exoplanets. For the above reasons, we shall focus mostly on the sources and sinks of P henceforth and explore the ensuing implications.

A strong case can also be made for Fe as the limiting nutrient (Boyd & Ellwood 2010; Tagliabue et al. 2017). It forms a central component of proteins used in respiration and photosynthesis, and enzymes involved in fixing nitrogen and using nitrates. Consequently, lower

levels of Fe could, in turn, lead to reduced growth rates and uptake of other nutrients (such as nitrogen) and thereby set limits on the total productivity. Apart from Fe, other trace metals such as molybdenum (Mo), manganese (Mn) and cobalt (Co) may also serve as the limiting nutrients (Anbar 2008), but the number of observational and theoretical studies of these elements is limited when compared to N, P and Fe.

3. SOURCES AND SINKS FOR THE LIMITING ELEMENTS

In order to maintain steady-state concentrations, it appears reasonable to suppose that the net inflow (sources) must balance the net outflow (sinks), as otherwise the nutrients would build up or be depleted over time. It is therefore instructive to consider the major sources and sinks on Earth, and ask whether they would be present on worlds with subsurface oceans.² Broadly speaking, the external inputs of nutrients to the oceans arise from three different sources on Earth: fluvial (from rivers), atmospheric and glacial. Of the three, the first two sources are much more important than the third (except for P) on Earth, as seen from Table 1 of Moore et al. (2013). However, neither riverine nor atmospheric inputs are directly accessible to worlds with subsurface oceans. Although each nutrient is depleted through different channels, the burial of organic sediments is a common sink (Schlesinger & Bernhardt 2013).

3.1. Phosphorus: sources and sinks

We continue our analysis by considering the sources and sinks of P. An important abiotic sink for P is hydrothermal activity (Paytan & McLaughlin 2007), which exists on Enceladus (Waite et al. 2017) and presumably on Europa as well. If one assumes that the hydrothermal flux of P removal is constant (Lingam & Loeb 2018), the rate of P depletion \mathcal{N}_P is given by

$$\mathcal{N}_P \sim -3 \times 10^{10} \text{ mol/yr} \left(\frac{R}{R_\oplus} \right)^2, \quad (2)$$

where R and R_\oplus are the radii of the subsurface world and Earth respectively, the normalization factor has been adopted from Wheat et al. (2003) and the negative sign indicates a sink.

Next, we turn our attention to abiotic source(s) for P. The primary source is expected to be submarine weathering (of felsic rock), but there is a crucial difference: on Earth, continental weathering is via rain water with a pH of 5.6 whereas submarine weathering occurs through

² We have addressed this issue briefly in Lingam & Loeb (2018), but elements other than P as well as abiotic sources were not considered there.

sea water, whose pH is assumed to be approximately 8.0. The dissolution rate per unit area (Γ) of phosphate-producing minerals can be estimated from

$$\log \Gamma = \log k_{H_+} - n_{H_+} \text{pH}, \quad (3)$$

where $\log k_{H_+} \approx -4.6$ is the logarithm of the intrinsic rate constant and $n_{H_+} \approx 0.9$ is the reaction order for combination of the minerals chlorapatite, merrillite, whitlockite and fluorapatite (Adcock et al. 2013). Denoting the dissolution rates on Earth and subsurface worlds by Γ_E and Γ_{SS} respectively, and introducing $\Delta = \text{pH}_{SS} - \text{pH}_E$ (where it must be recalled that $\text{pH}_E = 5.6$) and $\delta = \Gamma_{SS}/\Gamma_E$, we obtain

$$\log \delta = -0.9\Delta, \quad (4)$$

and if we use $\Delta \approx 2.4$ based on the above considerations, we find that $\delta \approx 7 \times 10^{-3}$. Estimating the dissolved preanthropogenic P input from continental weathering is difficult, and we adopt the value $\sim 3 \times 10^{10}$ mol/yr for the Earth that is consistent with Fig. 3 of Benitez-Nelson (2000); see also Seitzinger et al. (2010). Assuming that the area of weathered regions is proportional to the total area and using the above data, the net delivery of P to the ocean can be expressed as

$$\mathcal{N}_P \sim 3 \times 10^8 \text{ mol/yr} \left(\frac{\delta}{0.01} \right) \left(\frac{R}{R_\oplus} \right)^2, \quad (5)$$

and we have normalized δ by its characteristic value. From inspecting (2) and (5), it is apparent that the sink dominates over this source.

However, we wish to emphasize that (5) displays a very strong (i.e. exponential) dependence on the pH. In the case of Europa, it has been proposed oxidants formed on the surface via radiolysis are delivered to the subsurface ocean, where they react with sulphides and give rise to a highly acidic ocean with a pH of 2.6 (Pasek & Greenberg 2012). In this case, we obtain $\delta \approx 5 \times 10^2$, implying that (5) will be higher than (2) by 2-3 orders of magnitude. Although this bodes well from the standpoint of P alone, there are many detrimental effects arising from a highly acidic ocean, as discussed in Pasek & Greenberg (2012) and Lingam & Loeb (2018).

The situation is rendered very different when we consider Enceladus. A theoretical model concluded that the ocean comprised of a Na-Cl-CO₃ solution with a pH of ~ 11 -12 (Glein et al. 2015). The alkanine (high pH) nature of the ocean was argued to stem from the serpentinization of chondritic rock. If we choose a pH of 11, we find that $\delta \approx 1.4 \times 10^{-5}$, implying that (5) is about five orders of magnitude smaller than (2). In other words, the P sink overwhelmingly dominates the P source in this particular scenario. As a consequence, the limitation of P becomes potentially very important for Enceladus. Thus, the examples of Europa and Enceladus illustrate that δ can vary significantly and give rise to very different outcomes.

In Lingam & Loeb (2018), the possibility of a P source analogous to glacial weathering was considered, but its likelihood was deemed to be low for generic subsurface ocean worlds. Next, we turn our attention to an important *biotic* sink: the burial of organic sediments. Estimating this value is not an easy task, since the burial rate is subject to significantly spatio-temporal variability and dependent on a number of environmental factors. However, one can envision two general regimes:

Case I: If we assume that the burial rate is proportional to the biomass present in the oceans, the latter - and therefore the former - will depend on the availability of limiting nutrients. Hence, in this scenario, the amount of P removed through the burial of organic sediments would be commensurate with the amount of P being supplied (which is consumed in uptake by organisms), where the latter is given by (5).

Case II: Instead, we could suppose that the organic burial flux is proportional to the rate of sedimentation per unit area, based on Figure 9.11 of Schlesinger & Bernhardt (2013). If we further consider the idealized limit wherein sedimentation can be described by Stokes' Law (Guazzelli & Morris 2011), the settling velocity U of the particle is given by

$$U = \frac{2\Delta\rho a^2 g}{9\mu}, \quad (6)$$

where $\Delta\rho$ is the density difference between the particle and the fluid, a is the size of the particle, and μ is the viscosity of the fluid. We cannot estimate $\Delta\rho$ and a since these depend on organismal properties, and we therefore assume their characteristic values are similar to those on Earth; the value of μ is also taken to be approximately equal to that on Earth, since the medium (water) is the same. Thus, if the rate of sedimentation per unit area is proportional to U , we have $\Lambda_s \propto gR^2$, where Λ_s is the burial rate of organic sediments (in mol/yr) and the factor of R^2 represents the surface area. We use the scaling $M \propto R^{3.3}$ for icy worlds with $R < R_\oplus$ (Sotin et al. 2007) to obtain the final relation $\Lambda_s \propto R^{3.3}$. Thus, we can express the depletion of P via organic burial as

$$\mathcal{N}_P \sim -10^{11} \text{ mol/yr} \left(\frac{R}{R_\oplus} \right)^{3.3}, \quad (7)$$

where the normalization factor is the lower bound on the P removal via organic sediments on Earth (Paytan & McLaughlin 2007). This value, along with (2), is much larger than (5) for $\delta \lesssim 0.1$.

Although we do not know the total mass of P (\mathcal{M}_P) in the subsurface ocean, let us suppose that its concentration (in mol/L) is similar to Earth. This yields

$$\mathcal{M}_P \sim 8.6 \times 10^{14} \text{ mol} \left(\frac{R}{R_\oplus} \right)^2 \left(\frac{\mathcal{H}}{1 \text{ km}} \right), \quad (8)$$

where \mathcal{H} is the average ocean depth of the subsurface world, and the normalization follows from the fact that

Earth’s ocean (with $\mathcal{H}_\oplus \approx 3.7$ km) contains $\sim 3.2 \times 10^{15}$ moles of phosphorus (Benitez-Nelson 2000). If we consider subsurface worlds where the sinks are much more dominant than the sources, all the P in the ocean will be depleted over a timescale t_P given by

$$t_P \sim \frac{\mathcal{M}_P}{|\mathcal{N}_P|}, \quad (9)$$

and the denominator is given by (2) or (7). Let us consider only the former, which is abiotic in nature, since it represents a more robust estimate. Upon making use of (2), (8) and (9), we end up with

$$t_P \sim \frac{\mathcal{M}_P}{|\mathcal{N}_P|} \sim 2.9 \times 10^4 \text{ yr} \left(\frac{\mathcal{H}}{1 \text{ km}} \right). \quad (10)$$

Thus, in the case of Enceladus, choosing $\mathcal{H} \sim 30$ km, we obtain $t_P \sim 8.7 \times 10^5$ yr, implying that all the P in the ocean might be depleted over Myr timescales, which is very short by geological standards. This may turn out to be the bottleneck for the global existence of “life as we know it” on Enceladus.

3.2. Sources and sinks for other nutrients

We begin with a brief discussion of the sources and sinks for N. It is known that hydrothermal vents serve as sinks for P and several other trace metals and rare earth elements (Dick et al. 2013). However, these systems are ostensibly not an abiotic sink for N. As a result, we are left with two phenomena: submarine weathering and burial of organic material that would function as a source and a sink for N respectively.

To the best of our knowledge, we are not aware of studies that have been undertaken to estimate the dissolution rates for nitrate-producing minerals for different pH values. Hence, constructing the analog of (3) is not easy and the issues with estimating the burial rate have already been delineated earlier. However, a potential way for calculating the latter is to use (7) in conjunction with the Redfield ratio of N:P = 16:1 to obtain

$$\mathcal{N}_N \sim -1.6 \times 10^{12} \text{ mol/yr} \left(\frac{R}{R_\oplus} \right)^{3.3}, \quad (11)$$

where \mathcal{N}_N is the depletion rate of N. Although we cannot estimate the value of N addition due to submarine weathering, it appears likely to be lower than the corresponding value for continental weathering by rain water; if we consider the latter as approximated by the riverine input, it equals $\sim 10^{12}$ mol/yr for an Earth-sized world (Seitzinger et al. 2010). One can construct a depletion timescale for N along the lines of (9), but we shall not do so here since the estimates for N sinks and sources are arguably more uncertain than for P.

Next, we turn our attention to Fe. Although the major sources of dissolved Fe in the oceans are mineral dust (Jickells & Moore 2015) and sediments from subaerial

continental weathering, neither are likely to function on subsurface worlds. Instead, it would be necessary to consider the submarine weathering of Fe, which ought to depend on the pH. As we have not come across any detailed studies in this regard, it is not feasible to estimate this value. However, an interesting aspect of the iron cycle is that hydrothermal vents actually serve as a *source* of dissolved Fe (Tagliabue et al. 2010). Assuming that the hydrothermal flux of Fe is similar to that of Earth along the lines of (2), we obtain

$$\mathcal{N}_{\text{Fe}} \sim 9 \times 10^8 \text{ mol/yr} \left(\frac{R}{R_\oplus} \right)^2, \quad (12)$$

where \mathcal{N}_{Fe} is the addition/depletion rate of Fe, and the normalization is based on that of Earth (Tagliabue et al. 2010), although recent studies suggest that this value may be lower by about 20% (Fitzsimmons et al. 2014). Turning our attention to the sinks of Fe, the burial of organic sediments play a major role. As we have stated earlier, estimating this quantity is not an easy task because of its biotic nature. However, adopting the line of reasoning outlined in Case II yields

$$\mathcal{N}_{\text{Fe}} \sim -5.6 \times 10^{10} \text{ mol/yr} \left(\frac{R}{R_\oplus} \right)^{3.3}, \quad (13)$$

where the normalization (Earth’s value) has been adopted based on Figure 7 of Moore & Braucher (2008), but this factor is subject to some variability. At first glimpse, it appears as though (12) is much smaller than (13). However, when $R/R_\oplus \sim 0.04$, we find that the hydrothermal source would balance the sedimentary sink. As this condition is valid for Enceladus, it seems plausible that the issue of Fe limitation may not be as relevant as P limitation on sufficiently small icy worlds.

4. DETECTION OF BIOESSENTIAL ELEMENTS

Here, we will briefly discuss two important aspects of remotely searching for bioessential elements - based on our understanding of “life as we know it” - and the potential implications.

4.1. Stellar spectroscopy for bioessential elements

Given the importance of bioessential elements such as P in regulating ocean productivity, determining the stellar abundances of these elements could yield important information about the potential habitability of planets and moons orbiting the stars.

Several studies have already focused on determining P abundances for stars with varying values of [Fe/H] either via the near-ultraviolet P I doublet at 2135/2136 Å (Jacobson et al. 2014) or through the weak P I lines in the infrared at 10500-10820 Å (Caffau et al. 2011; Maas et al. 2017). Most of these studies obtained an average value of [P/Fe] of around 0.1 for stars in the metallicity range of $-1.0 < [\text{Fe}/\text{H}] < 0.2$. An interesting point worth noting from Figure 2 of Jacobson et al.

(2014) is that $[P/H]$ appears to be roughly proportional to the metallicity $[Fe/H]$ across several orders of magnitude.

Heavier bioessential elements - one notable example being Mo, which is discussed further below - are synthesized through a variety of mechanisms including the slow and rapid neutron-capture processes (the s- and r-process respectively) and the p-process. Recent evidence, based on LIGO’s gravitational wave detection of GW170817 (Abbott et al. 2017) and follow-up electromagnetic observations (Villar et al. 2017), implies that neutron star mergers play a dominant role in the production of r-processed elements (Kasen et al. 2017; Chornock et al. 2017). Since these events are spatially localized, the stellar abundances of such elements should vary considerably, and this is borne out by observations (Delgado Mena et al. 2017). Studies of metal-poor stars using the Mo I 3864 and 5506 Å spectral lines have revealed that the Mo/Fe ratio varies by more than two orders of magnitude, as seen from Figure 4 or Tables 4 and 5 of Hansen et al. (2014). It is therefore evident that habitable exoplanets with bioessential element abundances very different from that of Earth exist.

Thus, searching for spectral signatures of bioessential elements in stars known to host planets in the habitable zone may be viable and worth undertaking, but the following caveats must be borne in mind. First, the stellar and planetary abundances of bioessential elements will not necessarily be correlated since planets will typically have a wide range of compositions. Second, it does not always follow that the concentrations of these elements in the oceans will be proportional to their crustal abundances. For instance, only a tiny fraction ($\sim 10^{-4}$) of P on land or the ocean floor is actually present in the biosphere (Maciá 2005). Despite these issues, if the stellar abundances of P and other bioessential elements can be determined, we suggest that this path is worth pursuing.

Looking beyond bioessential elements, identifying the abundances of long-lived radioactive nuclides is also an important endeavor. Inferring the abundances of these elements, which are also expected to vary significantly across stars (Frebel 2010), may yield valuable information about the thickness of ice shells overlying putative subsurface ocean worlds and the potential mass of biospheres that can be supported by radiolysis (Lingam & Loeb 2018). For instance, it may be possible to measure the abundance of uranium via the U II spectral line at 3860 Å (Frebel et al. 2007).

4.2. Molybdenum and the clouds of Venus

Although the surface of Venus is uninhabitable for “life as we know it”, it may have been habitable until as recently as 0.715 Ga (Way et al. 2016). There have been many theoretical proposals in favor of aerial biospheres in the clouds of Venus (Morowitz & Sagan 1967; Schulze-Makuch et al. 2004; Limaye et al. 2018),

although significant challenges are posed by physico-chemical factors like acidity and solar radiation.

The composition of Venus’ clouds has been inferred through a combination of Earth-based observations, the Galileo orbiter and the Venus Express mission. None of these studies appear to have hitherto provided conclusive evidence for the availability of molybdenum (Mo) in the clouds (Marcq et al. 2018). Although the issue of whether Mo is truly necessary for “life as we know it” remains unsettled, the unique features of molybdenum chemistry and the presence of Mo in many essential enzymes suggests that it does constitute an essential biological element (Williams & Frausto Da Silva 2002). Hence, if the clouds of Venus possess insufficient concentrations of Mo - or perhaps tungsten (W), which serves as an effective substitute for Mo in certain enzymes (Hille 2002) - this environment may prove to be uninhabitable or possess oligotrophic biospheres that are not readily detectable. Hence, we propose that future missions to Venus, in addition to searching for biosignatures, ought to also carry instruments for detecting bioessential trace elements such as Mo.

5. CONCLUSIONS

The presence of elements necessary for biological functions (in Earth-based organisms) in sufficiently high concentrations constitutes one of the requirements for habitability. In this paper, we focused on identifying the putative elements that regulate total biological productivity on worlds with subsurface oceans; in theory, if these bioessential elements are absent, the oceans ought to be devoid of “life as we know it”.

We argued that the limiting nutrient for ocean productivity over long timescales is phosphorus (P). By quantifying the various biotic and abiotic sources and sinks for P, we concluded that the latter are potentially much more dominant over the former provided that the oceans’ pH $\gtrsim 8.0$; this condition is expected to be valid on Enceladus but not on Europa.³ In this scenario, we found that all the P in the oceans might be depleted over Myr timescales, thereby strongly inhibiting the prospects for the biochemistry of “life as we know it”. Our result is relatively robust since increasing the timescale by even two orders of magnitude would result in total P depletion over the age of the Solar system. We found that N and Fe could also prove to be limiting nutrients, but Fe sources and sinks may become comparable on small icy worlds with radii similar to Enceladus. We also hypothesized that the potential lack of molybdenum in the clouds of Venus can limit their biological potential. Lastly, we argued that stellar spectroscopy constitutes a useful tool for gauging the

³ Insofar the availability of P is concerned, we recommend that Europa ought to be assigned a higher priority compared to Enceladus.

chemical composition, and thus the biological potential, of exoplanets or exomoons around other stars.

Taken collectively, our analysis suggests that worlds with subsurface oceans are likely to have low global concentrations of nutrients. In other words, we expect local nutrient-rich biospheres to exist or global oligotrophic biospheres with low biomass densities. In both scenarios, the detection of life will be rendered difficult even provided that it is present. However, there are several caveats that must be borne in mind: our analysis made use of present-day values for the various sources and sinks, it does not account for the dynamical evolution of ocean biogeochemical cycles, and there may exist sources and sinks that are unique to subsurface ocean worlds and are mostly absent on Earth.

Although we predict that the detection of life is relatively unlikely because it would be either absent or

present in very low concentrations, this ought *not* be construed as grounds for ruling out future missions to subsurface worlds like Europa and Enceladus. In fact, we would argue the opposite because our central hypothesis is both falsifiable and testable: if life is detected in high concentrations, it falsifies our model and if the converse is true, our model might provide an explanation as to why many subsurface ocean worlds are not likely to be abodes for complex biospheres.

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