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Hypothesis Article

Minimum Units of Habitability and Their Abundance in the Universe

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Abstract

Although the search for habitability is a much-vaunted objective in the study of planetary environments, the material requirements for an environment to be habitable can be met with relatively few ingredients. In this hypothesis paper, the minimum material requirements for habitability are first re-evaluated, necessarily based on life "as we know it." From this vantage point, we explore examples of the minimum number of material requirements for habitable conditions to arise in a planetary environment, which we illustrate with "minimum habitability diagrams." These requirements raise the hypothesis that habitable conditions may be common throughout the universe. If the hypothesis was accepted, then the discovery of life would remain an important discovery, but habitable conditions on their own would be an unremarkable feature of the material universe. We discuss how minimum units of habitability provide a parsimonious way to consider the minimum number of geological inferences about a planetary body, and the minimum number of atmospheric components that must be measured, for example in the case of exoplanets, to be able to make assessments of habitability. Astrobiology 21, 481–489.

1. Reconsidering the Minimum Requirements for Habitability

What does it take to build a replicating, evolving entity that we would consider to be life? The minimum material requirements for life have generally been defined to be (1) a source of liquid water to act as a solvent for biochemical processes and reactions; (2) access to a bioavailable source of the following minimal number of elements: C, H, N, O, P, S to assemble the molecules required for cellular fabrication, growth, and replication; and (3) a source of biologically accessible energy to power cell repair, growth, and replication (Hoehler, 2007). In addition to the material requirements, life also requires physical and chemical conditions, such as temperature, radiation, ionic, and pH conditions that fall within the bounds for life. We discuss these later. All of these requirements are unavoidably defined by what we know about life on Earth.

We do not know whether the material requirements known for life on Earth are the minimum required in any type of life. For example, a recent hypothesis has been advanced that primordial cellular metabolic pathways might be assembled by using sulfur-dependent intermediates without the requirement for phosphorus-containing enzymes and energy carriers, such as ATP, that we associate with present-day life on Earth (Goldford *et al.,* 2017). This raises the possibility that CHNOS may be the minimum elemental constituents for life. In this article, P is retained as a basic requirement.

Noticeably missing from many previous definitions of habitability is the requirement for a fourth ingredient: transition metals. Transition metals, particularly iron, have ubiquitous roles in life in electron transport and as metal cofactors in enzymes and other molecules more specific to particular taxa, such as chlorophylls (Frausto da Silva and Williams, 2001). No organism is known that can grow and multiply without transition metals. It might have been possible to define iron, like CHNOPS elements, as a basic requirement for all life. However, the lactobacilli are reported to be able to grow without the element (Bruyneel *et al.,* 1989). Representatives of this bacterial genus seem capable of growing in media deprived of iron, resulting in cells with theoretically fewer than two Fe atoms per cell (Archibald, 1983), although it has been suggested that some iron is required for nucleotide metabolism (Elli *et al.,* 2000).

Adaptation against the use of iron in biochemistry is speculated to be linked to the selection advantage conferred by avoiding damaging iron-catalyzed oxygen free radicals.

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There is evidence that instead of iron, lactobacilli rely on Co- and Mn-cofactors in enzymatic processes (Sabine and Vaselekon, 1967; Weinberg, 1997), but the question of whether lactobacilli have some requirement for iron remains open. These observations show that even in the case of organisms where there is a putative ability to avoid the use of iron, the element is proposed to be replaced by a comparable ion with appropriate electron transport properties. Transition metals (TM) can be added to the list of basic requirements for life and to the minimum requirements for an environment to be habitable. The minimum elemental requirements for life could be revised as CHNOPS-TM.

2. Minimum "Units" of Habitability

What are the minimum material requirements that could give rise to a habitable environment? A minimum unit of habitability should provide the ingredients discussed in the previous section. To realize the minimum number of components, there should be a maximum overlap in the elemental requirements for life and the means of energy production; for example, a redox couple for energy acquisition should be available from the elements provided for CHNOPS-TM, thus minimizing the number of components in the system.

Figure 1 is an example of a geologically plausible theoretical minimum ''unit'' of habitability, assumed to exist within the physical and chemical limits for life, depicted as a ''minimum habitability diagram.'' In this example, we start with a lump of basaltic rock, a common igneous rock present on Earth, the Moon, Mars, and other rocky planets. The rock is immersed in liquid water, fulfilling the requirement for this solvent. A planetary crust containing such material implies the plausible presence of S, P, and Fe. The S is provided from sulfide minerals, which themselves form from chalcophile elements, such as Cu, Zn, but also Fe, which bind to S to produce sulfide phases, which distribute abundantly through rocky planet materials. Although sulfides have low solubility, through oxidation or slow dissolution they can provide biologically accessible S. The P is provided from a crystal of apatite. P is a lithophile element that strongly associates with O and becomes distributed through rocky planet materials as phosphates. The Fe is provided from an iron oxide crystal, fulfilling the requirement for a source of a transition metal (which can also be provided as the cation in iron sulfides). Although iron is a siderophile element, it distributes everywhere within rocky planets, with its abundance and redox state dependent on T and P conditions during core formation, the extent of oxidation via hydrogen escape and mantle redox disproportionation, and rate of supply from exogenous sources such as bolide impacts (Schaefer and Fegley, 2017). In addition to the minimum habitability requirements, it might be noted that basalt rocks also provide a range of other major and trace elements that can be used by organisms in a range of biochemical functions depending on the organism (*e.g.,* Na, Mg, Ca, Co, V).

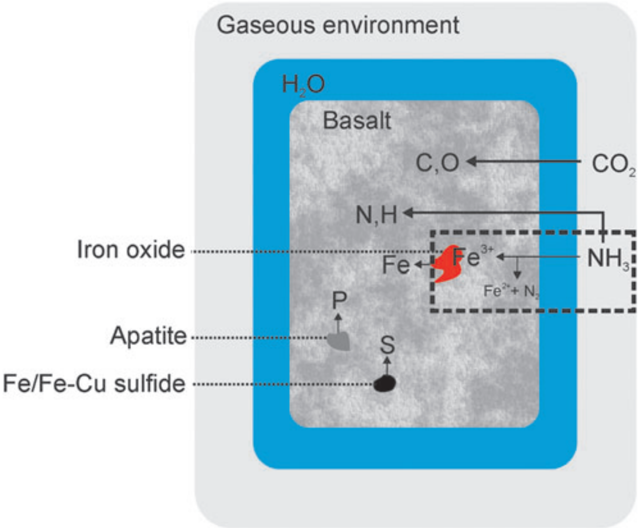

FIG. 1. A minimum habitability diagram. An example of a minimum habitability diagram showing the minimum material ingredients, colocated in a lump of rock, which would provide liquid water, CHNOPS-TM, and an energy source. The example shown is for habitability in a basaltic substrate using the feammox redox reaction. The horizontal dotted lines indicate minerals from which redox half reactions and/or CHNOPS-TM elements are derived. Solid lines indicate sources of redox half reactions and/or CHNOPS-TM elements or reaction pathways. The dashed box is the redox couple that provides biologically available energy. The minimum habitability diagram focuses on raw materials for life. As with Fig. 2, this diagram assumes that other physical and chemical conditions within the rock (*e.g.,* temperature, ionic conditions) are permissive for the growth and reproduction of known life.

To generate a habitable environment, a source of C and N is additionally required, and a redox couple for energy acquisition. First, the source of C could be derived from CO_2, a common primordial gas on rocky planets with weakly reducing atmospheres (Zahnle, 2006; Marty *et al.,* 2013). This gas would be assimilated by autotrophy. The CO_2 could be provided from carbonate minerals within the basalt, but these minerals would most likely have been derived from CO_2 at some earlier date. The availability of CO_2 depends on the redox state of the atmosphere and planetary interior, showing how the minimum units of habitability available in the universe will also depend on planetary redox evolution.

A source of N could be supplied through NH_3, another primordial volatile (Pizzarello *et al.,* 2011; Harries *et al.,* 2015; Yang *et al.* 2019), which would also supply a source of H atoms. Basalts can contain other sources of N, such as CN (Fisk and Giovannoni, 1999) and potentially fixed nitrogen compounds (NO_x), which are delivered into the crust after production in abiotic reactions such as impact events and lightning (Brandes *et al.,* 1998; Segura and Navarro-González, 2005; Summers and Khare, 2007; Manning *et al.,* 2009). NH_3 can also provide the electron acceptor for the final requirement for habitability—an energy source. NH_3 can be coupled with Fe^{3+} (the source of which was described earlier) as the electron acceptor in the microbial feammox reaction, recently described and demonstrated in an isolated microorganism (Huang and Jaffé, 2018). As with the case for CO_2, the availability of Fe^{3+} will depend on the planetary redox state and might be unavailable, or localized, on a highly reduced planetary body.

The minimum unit of habitability in Fig. 1 shows that, theoretically, the minimal material needs for habitability could be produced in a basaltic environment containing plausible S, P, and Fe-containing inclusions commonly found in igneous materials with the addition only of liquid water and C and N supplied to the system from two gases (CO_2 and NH_3) that are thought to be available in young anoxic planetary crusts.

Figure 2a shows a minimum unit of habitability in a planetary object with a chondritic composition, which might be the case for an icy moon, such as Saturn's moon Enceladus, or in asteroidal interiors (*e.g.,* Ceres). In this case, the supply of elemental requirements is similar to the basaltic substrate, except that P can be provided by, for example, chlorapatite or whitlockite (Fuchs, 1968) and S can be provided by Fe-Ni sulfides, which can additionally act as a source of transition metals (Zolensky and Thomas, 1995; McCubbin and Jones, 2005). An additional source of P could be schreibersite, $(Fe,Ni)_3P$, produced under reducing conditions.

Other minimum units of habitability can be envisioned. In Fig. 2b, S and P are again supplied by basaltic sulfide and phosphate-containing mineral inclusions. C is supplied by CO_2 autotrophy. The redox couple in this minimum habitability unit is associated with methanogenesis. The C source (CO_2) is the electron acceptor in the redox couple. The electron donor is hydrogen gas, produced by interaction of water with fayalite (olivine) in a serpentinization reaction, the fayalite additionally providing a source of iron (transition metal ions). The hydrogen provides the source of H atoms. In this case, N must be supplied to the system, which could come from any biologically accessible N source. As with the minimum unit shown in Figure 1, this unit of habitability is made possible by a basaltic substrate containing plausible mineral inclusions with the additional requirement only for water and an exogenous source of C and N.

Figure 2c shows yet another example. In this example, Fe is supplied by olivine as Fe^{2+}, which also acts as the electron donor in nitrate-dependent iron oxidation. An exogenous source of C (CO_2) and N is required, the latter provided by nitrate, which acts as the electron acceptor in anaerobic nitrate-dependent iron oxidation (Straub *et al.,* 1996). In this unit, apart from the source of C and N, all other requirements for habitability, including the redox electron donor, are provided by basaltic mineral inclusions.

The units of habitability described depend upon the colocation of all the requirements for life at the scale of microorganisms (micron scales). In the scenarios shown in

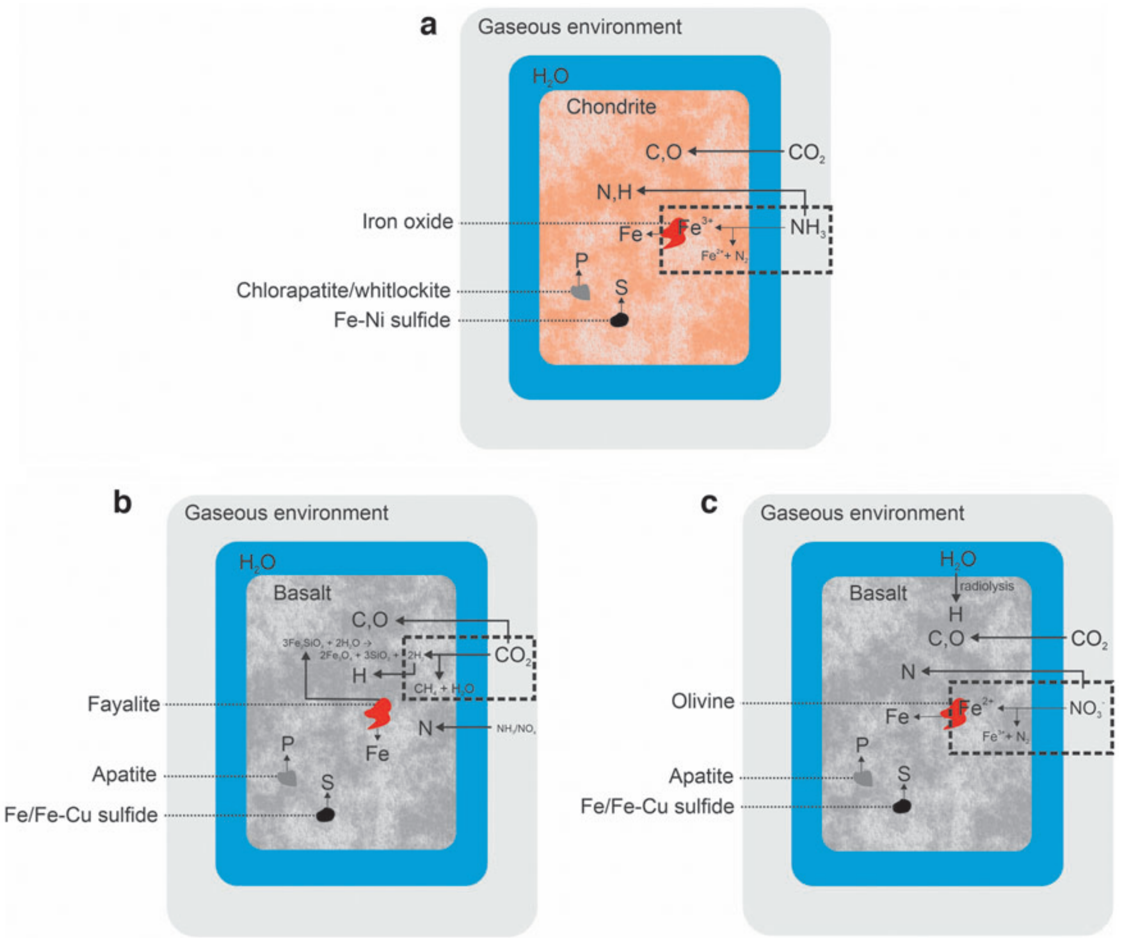

FIG. 2. Minimum habitability diagrams. Three other diagrams: (**a**) Minimum unit of habitability in carbonaceous chondrite rocks using the feammox reaction as the redox couple. (**b**) Minimum unit of habitability in igneous rocks using methanogenesis as the redox couple. (**c**) Minimum unit of habitability in igneous rocks using anaerobic iron oxidation as the redox couple.

Figures 1 and 2, this can be realized by the sufficient leaching of the mineral inclusions and provision of gases dissolved in water. A vigorous water flow through a rocky crust could theoretically provide sufficient continuous provision of gaseous components, and it would aid in overcoming the kinetic limitations on the provision of elements from solid minerals. Indeed, this scenario is suspected to allow for the habitability of Earth's deep crust (Fisk and Giovannoni, 1999; Pirajno and van Kranendonk, 2005).

Figure 1 does not include information on the temperature, ionic properties (including water activity and ionic strength), and pH of the H_2O or the rock, or other physical and chemical conditions that either individually or in combination limit life (Harrison *et al.,* 2013). The minimum habitability diagrams shown in this paper focus on the theoretical minimum raw materials for life, but for the diagrams to represent habitable conditions, they implicitly assume that all other physical and chemical conditions must fall within the limits of known life. This is unlikely to be the case on extreme runaway greenhouse Venus-like worlds or the surfaces of frozen planetary bodies, where planetary temperatures permanently lie outside the maximum (122°C; Takai *et al.,* 2008) and minimum (approximately -20°C; Junge *et al.,* 2004) temperature limits for known life. Thus, such regions can likely be discounted, based on current knowledge of life, as places for viable minimal units of habitability.

However, where temperatures do fall within the bounds for life and liquid water is present, many planetary bodies probably do have other physical and chemical conditions that are permissive for life (McKay, 2014). As on Earth, pH and ionic conditions are likely to be variable across most planetary bodies, shaping the theoretical suitability of environments for particular organisms but not rendering an entire planetary body uninhabitable. Even in a relatively homogenous ocean, interfaces, such as water-ice or water-rock interfaces, probably generate variations in these parameters. Extraterrestrial ultraviolet (UV) and ionizing radiation is usually screened by a planetary atmosphere or rocky materials, such that in the deep subsurface in most planetary bodies, it will not limit life (Mancinelli and Klovstad, 2000; Dartnell, 2011). Natural mineral radioactivity is unlikely to render an entire planetary body uninhabitable. Pressure modifies the growth of organisms, but no upper pressure limit for life has been defined, and low pressures ultimately inhibit habitability by rendering liquid water unstable, such as on the surface of Mars, which can be mitigated in the subsurface (Bartlett, 2002; Schwendner and Schuerger, 2020).

The minimal habitability unit must occur in an environment where the proposed redox couple (Figs. 1 and 2), or solar energy, is sufficient to allow an organism to conserve energy for growth and reproduction. Kinetic and other physical and chemical factors limit the thermodynamic favorability of redox reactions (Higgins and Cockell, 2020). However, when the physical and chemical conditions do not exceed the limits of life, a wide variety of favorable redox reactions are often available (*e.g.,* Sleep and Bird, 2007; Grotzinger *et al.,* 2013).

These first-order observations allow us to propose the hypothesis that within the pantheon of planetary bodies whose temperature conditions are suitable for life, with just a few primordial materials and assumptions about the solidification of accessory minerals in igneous and chondritic materials, we might expect habitable environments to be common in the universe. They further show how minimal habitability diagrams are useful for defining the first-order minimal set of materials that must be detected in life-detection missions or missions focused on detecting habitable conditions, a point we take up later for the case of exoplanets.

3. Are Habitable Spaces Pervasive in the Universe?

An illustration of the plausibility of these minimum units of habitability in extraterrestrial environments is to consider Saturn's icy moon Enceladus that harbors a subsurface water body. The composition of the core of Enceladus is not known, but whether it is basaltic (Fig. 1) or chondritic (Fig. 2a), the requirements within the core material for S, P, and Fe are likely to be met. S has been directly measured in plume material as H_2S (Waite *et al.,* 2009). Neither Fe nor P have been directly observed in the plumes, but the routes to the formation of igneous and chondritic material imply the existence of these two elements. For the two minimum gaseous ingredients (Figs. 1 and 2a), CO_2 and NH_3 were detected in the plumes of Enceladus by the Cassini Saturn Orbiter's Ion and Neutral Mass Spectrometer (INMS) at 0.053 ± 0.001 and $(8.2 \pm 0.2) \times 10^{-3}$ volume mixing ratio, respectively (Waite *et al.,* 2009).

In the case of Enceladus, other minimum units for habitability can be identified. For example, in the unit in Fig. 2b, serpentinization produces H_2 as an electron donor and H atoms. H_2 has been directly detected in the plumes of Enceladus (Waite *et al.,* 2017).

The presence of the theoretical requirements for a minimum unit of habitability cannot tell us whether all these requirements are colocated at the scale of microorganisms. For the minimum unit of habitability in Fig. 1, for instance, to exist on Enceladus, we must assume water circulation through the core sufficient to overcome kinetic barriers to the release of elements from core material and that there is circulation of CO_2 and NH_3 through the core material at sufficient concentrations to be biologically accessible. Evidence for the presence of active hydrothermalism on the moon suggests that core-ocean interaction does occur, and low core densities implied by Cassini gravitational field measurements suggest a porous core (Hsu *et al.,* 2015). If the gases detected in the plume are entrained in the ocean, then they may provide the necessary C, N, and H for the scenarios in Figs. 1 and 2a. Any scenario of core composition, whether basaltic or chondritic, implies sufficient concentrations of Fe and other transition metals, but the distribution of P and its biological availability is not known and could be limiting (Wordsworth and Pierrehumbert, 2013; Lingam and Loeb, 2018).

Currently, there is no reason to suggest that within the water body any minimum units for habitability would lie outside physical and chemical conditions for life (McKay *et al.,* 2014). Salinity, pH, radiation, and pressure conditions are not thought to be outside the known extreme limits for life. The presence of chemical conditions conducive to thermodynamically favorable redox couples needs further investigation, but based on our current knowledge that the moon hosts CO_2 and H_2 and organic material, it seems feasible that such couples exist (Taubner *et al.,* 2018).

Another case is Mars. Its primarily basaltic crust implies that habitable conditions associated with scenarios shown in Figs. 1, 2b, and 2c should exist. The presence of igneous-derived S and P-containing minerals have all been shown in abundance (Gendrin *et al.,* 2005; Poulet *et al.,* 2005; Bibring *et al.,* 2006; Ehlmann *et al.,* 2011; Grindrod *et al.,* 2012; Adcock *et al.,* 2013). Fe is present in both oxidized (*e.g.,* hematite) (Christensen *et al.,* 2001) and reduced (*e.g.,* olivine) (Mustard *et al.,* 2005) forms. The presence of liquid water on the surface of the planet today is contentious (Orosei *et al.,* 2018), but there is evidence for plentiful liquid water in the past (Carr, 2007; Lasue *et al.*, 2013). CO_2 is the dominant constituent of Mars' atmosphere today and may have been much more abundant in the past (Jakosky *et al.,* 2018). NH_3 has not been unequivocally detected in the martian atmosphere, and its presence in the early history of the planet is unknown, although the detection of fixed forms of nitrogen on the surface today (Stern *et al.,* 2015) suggests that breakdown of atmospheric N_2 occurs and could have been coupled to ammonia production in periods when the atmosphere was reducing in the past. The plausibility of the minimum unit of habitability shown in Fig. 1 would therefore depend on the early inventory of NH_3 (Kasting *et al.*, 1992), and this might be better known with improved modeling, showing how minimum units of habitability can provide motivation for filling in knowledge gaps of the abundance of specific chemical species.

The detection of fixed states of nitrogen in the martian soil (Stern *et al.,* 2015), and the presence of serpentine in Noachian terrains (Ehlmann *et al.,* 2010), suggesting the production of H_2, shows the plausibility of the widespread abundance of the scenario shown in Fig. 2b. The presence of reduced iron on Mars, abundant as olivine (Hamilton and Christensen, 2005; Mustard *et al.,* 2005), suggests the possibility of anaerobic iron oxidation shown in Fig. 2c.

Although the surface of present-day Mars is largely desiccated on account of the low atmospheric pressure, which lies on or near the triple point, there is good evidence that in the past many minimum units for habitability on the planet would have existed within physical and chemical conditions, including ionic and pH conditions, that were within the bounds for life (*e.g.,* Stoker *et al.*, 2010; Grotzinger *et al.,* 2013; Hurowitz *et al.,* 2017). The subsurface today may host physical and chemical conditions theoretically suitable for life (Michalski *et al.,* 2013).

Enceladus and Mars illustrate a general point. In planetary environments with igneous or chondritic composition, geological principles suggest we can infer the presence of potentially biologically available S, P, and Fe within the rocky matrix. Both CO_2 and NH_3 (Grady and Wright, 2006; Harries *et al.,* 2015) are primordial gases, present in many planetary atmospheres. Although the abundance of CO_2 and NH_3 and the redox state of Fe will depend on planetary redox states, photochemical processes, and other factors, the scenarios depicted in Fig. 1 and 2a may be common in the universe. Additionally, if atmospheric conditions lead to the fixation of N into oxidized forms by impact events, lightning, and hydrothermal activity, the scenarios in Fig. 2b and 2c become possible. Although the ingredients of units of habitability may be common, the frustration of the scenarios shown in Figs. 1 and 2 could be caused by various ways in which these ingredients for habitability can be separated or prevented from being colocated at the micron scales required by microorganisms, for example by kinetic barriers brought on by insufficient circulation of water.

The abundance and redox state of the minimal requirements for habitability will be significantly influenced by the bulk composition and structure of any given planetary body. Some exoplanets may be very different from planetary bodies in our own solar system, such as so-called carbide worlds (Nisr *et al.,* 2017). For example, planetary bodies in which the C inventory is relatively high may have graphite-dominated crusts, or Si-rich worlds may have silicon metal–dominated crusts. The consequences for habitability of these alternative compositions are not well understood (Sleep, 2018). However, as Sleep (2018) points out, Earth's crust is highly depleted in CNPS relative to primitive chondrites, yet it supports abundant life. Numerous indigenous chemical reactions and the extraterrestrial infall of material are likely to diversify the chemistry of graphite and silicon crusts, such that cycles of essential elements required by known life can be envisaged (Sleep, 2018). Thus, minimal units of habitability are likely to be possible on planetary bodies with quite different initial mineralogical inventories and surface and atmospheric conditions to those associated with the geological history of Earth.

4. Units of Habitability and the Search for Habitable Exoplanets

The definition of minimum units of habitability allows us to establish the minimum number of components that must be detected to infer exoplanet habitability. The discovery of Earth-mass planets around other stars can in theory be combined with measurements of the metallicity of the stellar environments to make certain assumptions about the composition of those planets (Dorn *et al.,* 2015). Models that use the condensation sequence of elements suggest the potential for exoplanet compositional variation (Thiabaud *et al.,* 2014). In particular, for example, C/O ratios of greater than 0.8 are predicted to lead to planets where Si is mainly located in carbides, while lower ratios result in the more familiar silicate minerals. The consequences for bioavailable CHNOPS elements are not clear. However, if an igneous composition similar to that of Earth, or a chondritic composition, can be inferred, then geological criteria, as above, can be used to infer the presence of S, P, and Fe. To minimally consider a planet to host potentially habitable environments requires the detection of H_2O, CO_2, and either NH_3 (Figs. 1 and 2a) or the detection of fixed nitrogen compounds (Fig. 2b, 2c). This applies to planetary bodies that fall within the temperature conditions for life (McKay, 2014) on which other physical and chemical conditions suitable for life, even if only locally, can be inferred.

In Fig. 3, we show a synthetic spectrum for an Earth-mass exoplanet Trappist-1e (Gillon *et al.,* 2017) in the habitable zone orbiting an M star observed by the conceptualized and proposed LUVOIR (Large Ultraviolet Optical and InfraRed surveyor) telescope (Roberge and Moustakas, 2018). We do not consider the photochemical stability of these gases, but use this spectrum to illustrate the general principle that the distinctive spectral lines of H_2O can be used to determine the presence of atmospheric water (although other factors such as planetary temperature or the presence or absence of

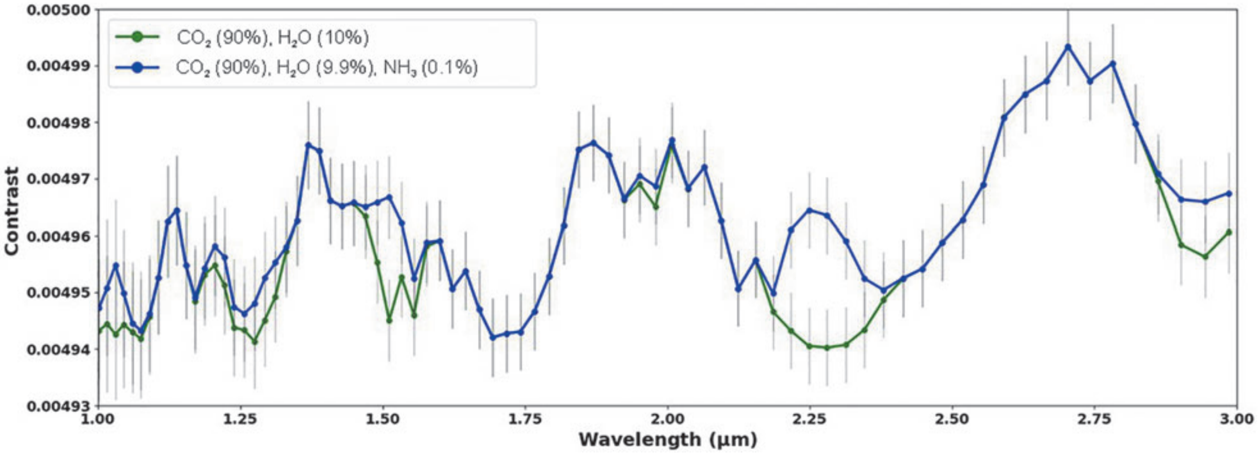

FIG. 3. Defining the minimum detection requirement to classify a planet as potentially habitable. In this plot, CO_2, H_2O, and NH_3 (blue curve) are the minimum atmospheric detection requirements to characterize habitable exoplanets. Synthetic spectra for the proposed LUVOIR telescope created via the NASA Planetary Spectrum Generator (Villanueva *et al.,* 2018) using the LUVOIR ExoTransit template for Trappist-1e with a simplified atmosphere with aerosols removed. All other material requirements for life can be geologically inferred (see text for details).

other gas species and aerosols [*e.g.,* Loftus *et al.,* 2019] must be observed to determine the likelihood of surface liquid water). CO_2 lines are sufficiently distinctive to infer the presence of this gas (and thus bioavailable C atoms), and the absorbance at 2.25 μm shows the presence of the required N atoms in the form of NH_3 gas. Once these are shown to exist, via techniques such as atmospheric retrievals where molecular abundances and temperature structure are inferred, all other requirements for habitability can be inferred assuming that Earth-similar composition allows inferences to be made on the availability of S, P, and transition metals without their direct observation. Thus, minimum units of habitability can provide a simplified approach to think about the minimum number of gases that must be detected and the minimum number of geological inferences that must be made to be able to make assessments about the habitability of exoplanets. As for planetary bodies in our own solar system, we would have to make the assumption that conditions were favorable for all the material requirements to be colocated at the scale of individual life-forms.

5. Conclusions on Minimum Habitability Assessments

The potential for habitable conditions on other planetary bodies is generally considered to be a remarkable possibility. This article has taken the approach of considering minimum units of habitability—the smallest number of material ingredients that can be provided to theoretically make an environment habitable to known forms of life. These conditions are likely to be met on Enceladus and Mars and may be met in other locations as well. Even the Moon (Schultze-Makuch and Crawford, 2018), a basaltic body that might have hosted water in its subsurface shortly after its formation and could have entrained within it primordial CO_2 and NH_3 before they were outgassed, could at micron scales have hosted units of habitability. Other candidates for hosting units of habitability are Ceres, Europa, and even a putative subsurface ocean of Pluto (Dalle Ore *et al.,* 2019). We propose the hypothesis that minimum units of habitability that sit within the physical and chemical conditions for life are common on planetary bodies across the universe.

In this article, four minimum units of habitability have been considered, but the detection of many other elements and compounds, particularly organics as potential electron donors and a source of C atoms (De Sanctis *et al.,* 2017; Eigenbrode *et al.,* 2018; Postberg *et al.,* 2018), lead to a greater number and complexity of these units and thus expand the abundance of habitable conditions in the universe.

This approach to habitability can aid us in considering what the minimum detection requirements are, with certain inferences about geological composition, for proposing the existence of units of habitable conditions on exoplanets. If we can detect H_2O, CO_2, and NH_3 (or other fixed nitrogen gases) in the atmospheres of rocky planets that fall within the temperature limits for life, then we may be able to assess the distribution of potentially habitable planets and test the hypothesis that habitable conditions are abundant using geological inferences without the direct detection of the other requirements for habitability.

It is not known whether habitable conditions imply the presence of life. There are scenarios by which habitable conditions can exist without life, for example on bodies too young to host an origin of life, or if the origin of life is a rare event (Cockell, 2011). The hypothesis of the widespread conditions for habitability in the universe could imply the presence of many habitable, though lifeless, environments.

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LUVOIR = Large Ultraviolet Optical and InfraRed surveyor
TM = transition metals