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Planetary Habitability Informed by Planet Formation and Exoplanet Demographics

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Abstract: Dozens of habitable zone, approximately earth-sized exoplanets are known today and many more are set to be discovered in the next decade. An emerging frontier of exoplanet studies is identifying which of these habitable zone, small planets are actually habitable (have all necessary conditions for life) and, of those, which are earth-like. Many parameters and processes influence habitability, ranging from the planet's orbit, to its detailed composition (including volatiles and organics), to the presence of geological activity and even plate tectonics. While some properties will soon be directly observable, others cannot be probed by remote sensing for the foreseeable future. Thus, statistical understanding of planetary systems' formation and evolution is a key supplement to the direct measurements of planets' properties. With over four thousand exoplanets discovered it is now possible to systematically test planet formation models against the emerging exoplanet demographics information. Probabilistically assessing the parameters we

cannot directly measure is essential for reliably assessing habitability, for prioritizing habitable-zone planets for follow-up, and for interpreting possible biosignatures. Here we review the key questions in planet formation that must be addressed to improve the predictive power of planet formation models. We will also discuss how Bayesian assessment of a planet's habitability provides a tool for combining statistical contextual knowledge on the exoplanet population with specific – but necessarily uncertain and incomplete – information on the individual planet.

RELATIONSHIP TO THE NAS EXOPLANET STRATEGY REPORT: *This white paper is consistent with the general recommendations of the NAS Exoplanet Strategy Report, but focuses on a different, novel approach for integrating multi-disciplinary and multi-field knowledge in a consistent framework to provide Bayesian assessment for planetary habitability.*

Key Parameters Often Not Directly Observable

Remote sensing surveys for life beyond the solar system will likely be limited to biosignatures originating from surface or near-surface life, for the lack of efficient ways to probe sub-surface and deep ocean habitats. For a planetary surface to be *habitable* it must not only allow for liquid water to exist but the planet and planetary system must provide all conditions necessary for life. Therefore, surface habitability requires the availability of chemical ingredients necessary for life, the presence of an atmosphere, and a relatively stable planetary climate.

Multiple key parameters with direct impact on planetary habitability do not lend themselves to remote-sensing measurements in the foreseeable future. Constraining or determining these parameters can often be best achieved by understanding the formation and evolution of the planet, and its interactions with the host star, and the evolution of its host planetary system. The most obvious such parameters are the detailed bulk composition (Si, Fe, Mg, C, H, O, N) of the planet, including the planetary volatile and organics budgets. (Although bulk density constraints may allow the identification of *clearly non-earth-like* planets, the degeneracies inherent to the equations of state for different possible compositions do not allow identifying habitable planets in general). Another example is geological activity, important for planetary habitability by providing a very large buffer for the atmosphere. However, the presence or absence of earth-like composition and processes can be predicted probabilistically if the formation history and bulk composition of the planet are reasonably well established.

1 Importance of Planet Formation and Evolution

We bring two examples for the importance of understanding planet formation and evolution for establishing a planet's habitability:

Proxima Centaturi b: This indirectly discovered habitable zone planet [4] is a good example for the kind of information that should be available for future potentially habitable exoplanets and the evaluation process these and future detections will require. Little is known about the planet itself: only its orbital period, equilibrium temperature, an $m\sin(i)$ measurement, and a loose constraint on orbital eccentricity are available. Much more is known about the host star Proxima Centauri and about the population of close-in small planets around M dwarf stars. In-depth models of Proxima b often assumed it to be a rocky planet with the minimum allowed mass (from the $m\sin(i)$ measurement) without considering either the uncertainty of the measured value, the fact that it represents a lower limit, or the fact that its nature (rocky, icy, gaseous planet) is yet undetermined. Similarly, the formation and evolution of the planet is not understood.

A different approach was advocated for by [9]. In this study probability distributions representing observational constraints (both specific to the individual system as well as derived from population statistics of close-in M dwarf exoplanets) were combined. Indeed, because several of the underlying probability distributions are asymmetric (and some are very broad) the nature of the planet is not straightforward to determine. In fact, that study found a broad probability distribution (with 10-15% likelihood for Proxima Centauri b being a sub-neptune planet) and an expectation value for its mass that is significantly higher than the measured $msin(i)$ value and with a very asymmetric uncertainty.

Future studies of habitable exoplanets will most likely have to interpret the nature of individual planets by combining specific information (on the planet itself, the host star, and other planets in *the system) with prior distributions of planet properties gained from exoplanet population studies (distributions of orbital elements; mass distribution) and with predicted outcomes from planet formation models (volatile content, possible range of atmospheric loss, migration history, etc.).*

TRAPPIST-1 planets: The recently discovered roughly earth-sized planets in the habitable zone of TRAPPIST-1 [17] offer other examples for the challenges posed by the limited information available on such worlds. Up to three of the planets may be in the present-day habitable zone. The observed properties of the planets (mass, density) provide important, but limited insights [18]. However, considering the properties of the exoplanet population and possible formation/evolution histories of the system is very likely to unveil major differences between the otherwise similar planets (e.g., [35]) and help identify one as the best target in which to invest JWST time. Thus, TRAPPIST-1 is another system where the information coming directly from the planets must be complemented by the much greater but more general body of information (context) emerging from planet formation and exoplanet population studies.

Allocating major resources - such as telescope time - for follow-up observations of planets based *purely* on directly observed properties (e.g., deepest transit depth or signal-to-noise ratio) is neither a conservative nor efficient approach: the implicit assumption behind such a decision would be that all planets of similar sizes (regardless of differences in their other parameters) are essentially the same – an assumption we already know to be wrong, as there are clear correlations between planet and system properties (e.g. [26, 28, 30], EXOPAG SAG13 Report).

2 Key Challenges in Planetary System Formation

In this section we briefly review the key challenges in planet formation and planetary system evolution as they relate to planetary habitability assessments.

- **How do Planetesimals form?** The growth of initially submicron-sized grains to 10^3 km-sized planetesimals represents a critical, but poorly understood phase in planet formation. From radioactive dating of iron meteorites (surviving fragments of cores of differentiated minor bodies) it is clear that this growth phase was rapid ($\sim 10^5$ yr) in the Solar System [5], but planetesimals in other planet-forming disks remain undetectable. Multiple lines of evidence suggest that planetesimals do not grow via pairwise, constructive collisions, but via another, faster and more efficient process. The internal structure of the primitive Solar System materials (sharply peaked size distribution, lack of units with sizes greater than 10^{-2}m, evidence for rapid assembly) lends further support to this conclusion.

  Multiple mechanisms have been put forward to explain rapid planetesimal formation, including streaming instability [23, 7, 11], pressure-induced dust traps, eddies, and vortices [25, 12], and gravitational instability [36].

  Understanding planetesimal formation is important for planetary habitability because all solids in rocky planets must pass through the planetesimal stage before being accreted (either early or late). Therefore, the physical process responsible for planetesimal formation will likely also affect the entirety of the solids that will eventually build rocky planets, probably influencing the intrinsic volatile and organics budgets of rocky planets (e.g., [5, 33]).

- **How do protoplanetary disks and forming planets co-evolve?** Protoplanetary disks are dynamic objects, through which mass is transported inward and accreted by their host stars.

Evidence for this dynamic evolution is found in astronomical observations, where the infall of material from the disk to the star is observed [e.g. 20] as well as in primitive bodies in our Solar System, such as chondritic meteorites, where materials from very disparate disk environments are mixed together on fine (sub-millimeter) scales [e.g. 24]. Together, these lines of evidence suggest that this dynamic evolution occurred over timescales of millions of years, and was fundamental in controlling how the earliest stages of planet formation proceed.

How the physical properties of a disk change as a result of this dynamic evolution determines the properties of the planets that will eventually emerge. Whether the mass transport is driven by disk winds [6] or viscous evolution [19], the loss of mass over time, combined with dust growth and settling, will lead to continuously evolving pressures, temperatures, and radiation fluxes within the disk. Further, the transport of mass and redistribution of angular momentum that must accompany it, along with interactions between the gas and dust within the disk, will drive large-scale redistribution of solids prior to their incorporation into planets. As a result, solids will be exposed to a wide array of disk environments, with their chemical evolution being determined by the integrated path, and set of environments, that they are exposed to within the disk [13]. This coupled physical and chemical evolution will ultimately determine what compounds are available as solids to be delivered to planets.

- **Was the proto-solar nebula a typical protoplanetary disk?** Solar system planets and minor bodies are relics of the protoplanetary disk around the young sun. The mass, composition, and location of the planets can be used to reconstruct a *Minimum Mass Solar Nebula* (MMSN) the amount of material that must at least have been present in the sun's protoplanetary disk at different heliocentric distances [22]. The MMSN provides a reference point for comparing the solar system with protoplanetary disk observations.

  The mass and radial distribution of material in protoplanetary disks can be estimated from millimeter-wave observations. Spatially resolved millimeter-bright protoplanetary disks indicate that the disk mass in the outer ($\gtrsim 10$ au) regions is consistent with the MMSN [3]. The radial distribution of material is typically less centrally peaked than the MMSN (e.g., [37]). Larger surveys at lower spatial resolution indicate that the typical protoplanetary disk around a solar-mass star is less massive than the MMSN with $\sim 10 M_\oplus$ of dust (e.g., [32]). Observations with ALMA are expected to provide direct constraints on the dust mass and indirect constraints on the gas mass in the giant planet-forming regions ($\sim 1 - 10$ au). An understanding of disk evolution, or direct probes of the early phase of protoplanetary disks, are needed to place the solar system in the context of planet forming regions around other stars.

- **What processes disperse protoplanetary disks?** It is well established that the lifetime of protoplanetary disks is a few Myr (e.g., [16, 34]) and that by ~10 Myr most disks do not have enough gas to form Jupiter-mass planets (e.g., [31]). Furthermore, with only ~10% of young disks showing evidence of partial clearing (e.g., [15]) the transition between disk-bearing and disk-less appears to be much shorter than the disk lifetime, only a few $100,000$ years. Disk evolution and dispersal directly impact the formation and evolution of planetary systems. Disk winds, in combination with dust growth and settling, increase the dust-to-gas mass ratio in the disk midplane, which promotes the formation of planetesimals (e.g.

[10]). In addition, the preferential removal of H/He rich gas by photoevaporation could result in the gradual enrichment of refractory elements and may be necessary to explain the formation of Jupiter and Saturn with all their constraints (e.g. [2]). Gas removal ends giant planet formation and stops planet migration. MHD and thermal winds may be also needed to explain the two populations of hot and cool Jupiters [14] and influence the migration of planetary embryos, hence impact what type of planets can form in a disk (e.g. [21]).

- **How are volatiles and organics delivered to habitable zone planets?** While 70% of Earth's surface is covered by water, this critical compound makes up just $\sim$0.1% of the total mass of the planet. The low mass suggests that water was delivered by the accretion of more volatile-rich bodies that formed further out in the Solar System, beyond the snow line, where water was able to condense as a solid and be incorporated into planetesimals. At the same time, the D/H ratios of water on Earth indicate a partly asteroidal source of water [1]. Further, life on Earth requires sufficient delivery of biocritical elements C and N as they are important in biological reactions and atmospheric gases which regulate the temperature and pressure at the surface of the Earth. Like water, the carriers for the primary carriers for elements are largely expected to have been too volatile to exist as solids where the Earth formed, suggesting delivery of material from more distant regions of the Solar System. As of yet the source of Earth's volatiles and their delivery mechanism is poorly understood and it remains unclear to what extent was Earth's formation and evolution represtenative to other Earth-sized planets; yet, the availability of volatiles (and any connection to system parameters) remains a core question in planetary habitability.

- **How do planetary building blocks and planets migrate?**

  The Kepler prime mission has revealed that the occurrence rate of planets in the inner planetary systems (d<50 d) is very high, demonstrating that most planetary systems have orders of magnitude more mass in their interiors than the solar system. Furthermore, stellar-mass dependent analysis of the Kepler exoplanet population demonstrated that low-mass stars have more small planets *and more* mass in solids on short-period orbits than more massive stars, a trend that runs opposite to the stellar-mass dependence of disk masses [27]. These findings strongly argue for the re-distribution of solids in the forming planetary systems: either in the form of the transport of planetary building blocks or via migration of planets. *Understanding how planets and planetary building blocks are re-arranged during and after formation is essential to explaining fully-formed planetary systems.*

3 Integrating Planet Formation, Exoplanet Demographics, and Exoplanet Observations

The next decade will see exoplanet characterization move from considering individual measurements of a specific planet to a Bayesian framework that combines specific but uncertain measurements of the properties of individual planets with well-established, but general (statistical) contextual information from exoplanet demographics and planet formation.

Assessing the habitability of any specific planet will require assessing a number of factors, each of which can be represented by a probability distribution. These probability distributions can be combined to provide a comprehensive Bayesian assessment of the planets' habitability (e.g., [9]).

Two key advantages of this approach is that: i) it provides more realistic treatment of the factors than just working with their expectation values and their uncertainties, and ii) it allows combining constraints specific to the individual planet with probabilistic information derived from exoplanet population and planet formation studies.

We see the following opportunities to advance this important process:

i): Developing a statistically predictive model for planet formation is now both within reach and critically important to allow system-level predictions for exoplanets, with particular emphasis on parameters not directly observable.

ii) WFIRST. WFIRST's primary exoplanetary mission is a near-infrared wide-field survey to detect and characterize planets from the habitable zone out to unbound planets using gravitational microlensing [8]. This survey will test planet formation models through the anticipated large number statistics of sub-Mars mass planets and planets beyond the snowline. WFIRST is uniquely capable of detecting sub-Mars mass planets and is expected to detect about 10–30 super-Earths, with the precise number being of particularly high discriminatory value between existing planet formation model [29].

iii) US ELT Program: Planet formation studies combine a broad range of observations, most of which are limited by spatial resolution (telescope diameter) and by spectral resolution/sensitivity. 30m-class telescopes are required to provide an order-of-magnitude improvement in the sharpness of the images of forming and accreting planets and related disk structures; to directly measure accretion rates of forming jovian and sub-jovian planets; and to image exoplanets in the outer planetary systems, mostly unexplored as of now. ELT spectroscopy will allow measuring accretion *and* mass loss rates (due to photoevaporation and winds).

iv) LUVOIR will have the spatial resolution to probe $\sim$1 au at the distance of nearby star-forming regions like Taurus. This resolution, combined with improved sensitivity at UV/optical wavelengths, will enable to directly detect accreting protoplanets with masses down to Saturn and image the narrow ($\sim$1-10AU) gaps carved by Neptune mass planets. With 40 times higher sensitivity at UV wavelengths and multi-object spectroscopic capabilities, LUVOIR will efficiently survey the entire Orion complex, trace the evolution and dispersal of the main molecular carriers of C, H, and O during planet assembly, trace molecular and low-ionization metals from disk winds, and determine the absolute abundance patterns in the disk as a function of age.

v) Origins Space Telescope: With more than 1,000 times higher line sensitivity compared to previous far-infrared observatories, OST will efficiently survey 1,000 planet-forming disks around stars of all masses and evolutionary stage to map their total water content using rotational water lines. The same survey will also measure the disk gas masses using the ground-state line of HD at 112 μm as a direct proxy for H_2. The global volatile content and unbiased molecular gas mass of complete disk populations will be critical and unique inputs to any planet-formation model. The design reference disk survey will cover the 30-600 μm range, opening up a large new discovery space of disk gas tracers beyond water and HD. OST will also survey the water D/H ratio in tens of solar system comets, allowing comparisons between volatile content of the solar nebula and that revealed by the disk survey.

vi) Research grants supporting multi-investigator, multi-disciplinary projects. Due to the multi-disciplinary nature of planet formation and evolution single-investigator grants can only focus on individual facets of the challenge. While these efforts are essential, larger-scale opportunities *integrating* knowledge and methodology gained from narrowly focused investigations are necessary to advance the understanding of planet formation to the required levels.

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