The Search for Habitable Environments and Life in the Universe

The NASA Astrobiology Institute
Habitability and Astronomical Biosignatures Focus Group

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Introduction

In the vast blackness of space, our home planet is a sparkling oasis of life. Whether the Universe harbors other worlds that can support even simple life is a question that has been pondered, yet remained unanswered, for over two thousand years. The next steps in answering this question are to detect planets outside our solar system, characterize their habitability, and ultimately examine their atmospheres and surfaces for evidence of life.

The search for life beyond the Solar System is one of the fundamental areas of study in astrobiology. The goals and objectives of this science are given in Goals 1 and 7 of the 2008 NASA Astrobiology Roadmap (Des Marais et al., 2008). Goal 1 seeks to understand the nature and distribution of habitable environments in the Universe, to determine the potential for habitable planets beyond the Solar System, and to characterize those that are observable. Goal 7 includes scientific objectives on determining how to recognize signatures of life in the atmospheres and on the surfaces of distant worlds.

In practice, to search for signs of habitability and life on the observable surfaces and atmospheres of potentially habitable planets we must focus on planets around stars in the Solar neighborhood. This need arises from the astronomical challenges inherent in characterizing these worlds, specifically the requirement to sufficiently suppress the light from the parent star and angularly separate the planet so that its photons can be isolated. Recent developments in observational technology suggest that the sensitivity required to directly detect and characterize terrestrial planets around other nearby stars is being approached (e.g. Trauger & Traub, 2007).

As astronomical observing capability improves, more ambitious science goals can be achieved. Initial measurements of mass, radius and orbital parameters will constrain habitability, and identify targets for detailed follow-up. Subsequent missions should attempt to collect time-resolved photometric measurements at multiple wavelengths throughout the visible and near-infrared (NIR) to infer planetary surface and atmospheric properties, such as the presence of oceans, clouds, or continents. Since extrasolar terrestrial planets may be as unexpectedly diverse as their Jovian counterparts, for these planets spectroscopy will provide the least ambiguous characterization of their environments. With temporally-resolved spectra, even if disk-averaged, compositional and environmental properties can be constrained, and a search can be made for the global changes in a planet's atmosphere and surface that are produced by life processes.

In this white paper, we identify three science themes that are compelling scientific frontiers for the next decade. These themes are: The Diversity of Extrasolar Terrestrial Planets, The Habitability of Extrasolar Terrestrial Planets, and the Search for Life Beyond the Solar System.

The Diversity of Extrasolar Terrestrial Planets

Extrasolar terrestrial planets are likely to exhibit diversity that is greater than that seen for the current extrasolar Jovian population. In the past 10 years we have seen the number of known extrasolar planets grow from a handful to over 300. These (mostly Jovian) planets were found in unexpected orbits, and many with densities and thermal characteristics unlike any in our Solar System. Their discovery has challenged and ultimately improved our understanding of planet formation, planetary migration, planetary dynamics, and planetary atmospheric science. The recent discovery of a handful of both hot, and potentially habitable, super-Earth planets, with masses between 3-10 $M_\oplus$ provides our first window into the extrasolar terrestrial planet population, and already provides examples of terrestrial planets beyond the sample found in our Solar System. Diversity will likely be found in initial properties and planetary system environment, and in subsequent evolution. The Earth's geological activity, atmospheric composition and biosphere have changed dramatically over the last 4.6 billion years, and Venus, Earth and Mars exhibit markedly divergent evolutionary trajectories in their environmental properties. By detecting and characterizing terrestrial planets orbiting nearby stars with ages ranging from a few million to 10 billion years, we also gain the opportunity to improve our understanding of terrestrial planet evolution at diverse stages of development.

Kepler will provide statistical measurements of the prevalence and size distribution of (out to 800pc distant) extrasolar terrestrial planets, potentially discovering true Earth analogs (an Earth mass planet in an Earth-like orbit). The frequency of terrestrial planets around main sequence stars provided by *Kepler* and ongoing detections via microlensing, will inform our subsequent attempts to detect and characterize extrasolar terrestrial planets in the local Solar neighborhood.

Detection and characterization of super-Earths is a high priority to determine their mass distribution, and to study environmental characteristics at different stages of evolution. Super-Earths have no analog in our Solar System, and our understanding of their geophysical and atmospheric attributes, including solid body composition, ability to support plate tectonics, the rate of volcanism, the relative amounts of oceanic and continental surface coverage, the source and nature of their atmospheres, including the balance between volcanism, escape and retention of primordial gas, and the resulting redox state of the surface, are completely unknown.

The Habitability of Extrasolar Terrestrial Planets

For the purposes of remote-sensing over astronomical distances, extrasolar terrestrial planets are considered to be "habitable" if they are able to maintain liquid water on their surfaces. While we acknowledge that subsurface biospheres are possible on worlds without surface liquid water, such as Mars and Europa, the impact of a subsurface biosphere on the observable planetary surface and atmosphere is likely significantly less than a surface biosphere's. Consequently we focus here on detection of *surface* habitability and biospheres as the higher priority for the coming decade. Orbiting within the habitable zone is not sufficient for surface habitability, however. Other conditions, such as a poor water inventory at formation, or insufficient mass to retain an atmosphere and ocean can preclude planetary habitability, even within the habitable zone. Two measurement approaches can be used to determine whether a planet can support liquid surface water. The first directly detects surface water using phase-dependent ocean glint, time-dependent multi-wavelength photometry, or polarization. The second implicitly determines the presence of liquid water by determining mass, orbit, and surface and atmospheric properties.

Direct Detection of Large Bodies of Liquid Water

Planets with large bodies of liquid water will reflect light from the parent star differently than planets without. As an extrasolar planet goes through phases, specular reflectance from an ocean becomes a larger fraction of the starlit portion of the visible disk. Recent simulations have shown that planets with oceans could exhibit anomalous phase-dependent disk-averaged lightcurves (Williams and Gaidos, 2008; Fig 1). Recent work by Cowan et al., (2008) has used principal component analysis to analyze temporally-resolved multi-wavelength disk-averaged photometry of the Earth as seen by the NASA EPOXI spacecraft. Their analysis indicates that with this type of dataset, it is possible to identify the spatial dominance of a “blue” and a “red” spectrum at different points in the Earth’s rotation. While the generic “blue” spectrum could also derive from Rayleigh scattering from a planet with clouds and a dense atmosphere, it would provide a first order indication that a planet is a prime candidate for spectroscopic follow-up. Polarimetry could also be used to detect reflectance from the ocean surface, or the presence of water rainbows as a function of disk-averaged phase-dependent observations (Bailey 2007).

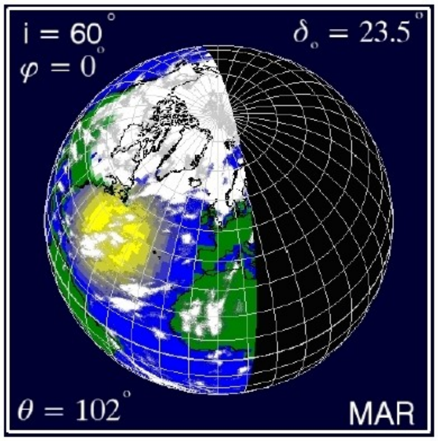

Figure 1 - Model view of Earth showing with sunlight (yellow) glinting off the Atlantic ocean basin. From Williams and Gaidos, 2008.

Characterization of the Planetary Environment

As a complement to directly detecting liquid water, the comprehensive characterization of an extrasolar terrestrial planetary environment also constrains the planet’s potential habitability. The principal planetary characteristics that govern habitability are planetary mass, orbital parameters, bulk atmospheric and surface composition, and the presence and abundance of greenhouse gases.

Planetary Mass

Planetary mass is a key determinant of planetary habitability and the maintenance of habitability over time. Planetary mass constrains the initial amount of geological planetary heat and its loss rate over time. High geothermal heat can maintain a liquid core, crucial for the generation of planetary magnetic fields, which protect a planetary atmosphere from stellar wind ablation. Geothermal heat flux also determines the nature and magnitude of volcanic and plate tectonic activity, which can buffer the long-term climate of a planet. The mass of the planet governs atmospheric escape rates and the evolution and long-term retention of the planetary atmosphere.

Orbital Parameters

The shape and size of a planet's orbit, and the interaction between planet and star via both radiation and gravitational energy, play critical roles in determining a planet's surface temperature, and its potential to maintain liquid water on the surface (Kasting et al. 1993; Williams & Pollard 2002; Barnes et al. 2008). Existing 1-D climate models indicate that too much or too little radiation leads to climate catastrophes at the inner and outer edge of the habitable zone (HZ) (Kasting et al. 1993; Selsis et al. 2007). Future work will examine the detailed radiative effect of clouds, and use 3-D climate models to further refine the HZ limits.

Orbital dynamics of a system may also impact the energy reaching the planetary surface from below, via strong tidal evolution (Rasio et al. 1996; Jackson et al. 2008a, 2008b) that can change the orbit over time and deposit large amounts of energy into the planetary interior. These processes can limit the time a planet is in the habitable zone (Barnes et al. 2008), as well as drive sterilizing volcanism (Jackson et al. 2008a), or conversely provide energy for plate tectonics and long-term climate stability on smaller planets. For planets which are part of a larger system, gravitational perturbations may lead to dramatic eccentricity cycles, which in turn drive periodic variations in surface temperature, rotation rate, insolation, and tidal heating. Non-linear feedback cycles between a planet's atmosphere and interior are a likely consequence of such complexity.

M dwarf habitable zones are close to the star, subjecting a planet within it to both strong UV fluxes and the potential for tidal locking. While all young stars emit proportionally more UV and harder radiation (Pace and Pasquini, 2004), M dwarfs have particularly intense flares. This early UV bombardment isn't considered in classical habitable zone calculations, yet may drive early irreversible hydrodynamic escape of planetary atmospheres (Tian and Seager, 2008). Tidal locking must also be considered in M dwarf habitability determinations, with planets on circular orbits likely exhibiting permanent daysides and nightsides. Planets on eccentric orbits however, can rotate at a well-defined rate and escape this fate (Barnes et al. 2008; Correia et al 2008).

Atmospheric Conditions

Although mass, density and orbital parameters help to constrain planetary habitability, a definitive determination of whether a planet can support liquid water on its surface requires characterization of the planet's atmosphere, and if possible, its surface. Attempts to directly measure planetary temperature by obtaining mid-infrared (MIR) brightness observations will measure the temperature of the effective emitting layer, which may not be the planetary surface. In our Solar System, Earth and Venus return global effective temperatures 17K and 430K lower than their actual surface temperatures. This discrepancy between measured effective and surface temperatures is due to the greenhouse effect on the planet. Using a combination of measurements and models, the greenhouse effect can be determined by detecting and quantifying greenhouse gases in the planetary atmosphere (c.f. Fig 2c,d), and inputting those constraints into an atmospheric climate model that will calculate greenhouse effect and surface temperature.

The Search for Life Beyond the Solar System

To maximize the probability that we can detect the presence of a biosphere in disk-averaged data from a nearby extrasolar terrestrial planet, that planet's life will need to be global, on the surface of the planet, and of sufficiently long tenure that it will have significantly impacted environmental conditions. On Earth, signs of life's impact consist of three types: *atmospheric biosignatures* composed of biologically-produced species in disequilibrium with the rest of the environment; *surface biosignatures* marked by enhanced reflectivity longward of wavelengths used for photosynthesis; and *temporal biosignatures* that include biologically driven seasonal variations in atmospheric composition or surface albedo. On Earth, oxygenic photosynthesis dominates the biosphere, but this has only been the case for approximately half of the Earth's history. Even today, alternate metabolisms flourish, including non-oxygenic photosynthesis, and chemosynthesis that uses chemical energy sources instead of light energy.

Photosynthetic biosignatures

Photosynthesis on Earth produces the most detectable signs of life at the global scale. The presence of oxygen or ozone in an atmosphere simultaneously with reduced gases like methane is considered a robust biosignature (Des Marais et al., 2002), and the ability to detect it should be a priority for life-finding missions. Potential false positives for this biosignature have been addressed (Kasting, 1997; Leger et al. 1999; Segura et al. 2007), and should continue to be explored. A challenging, complementary observation to atmospheric oxygen would be detection of the vegetation red edge - the strong contrast in red absorbance and near-infrared reflectance of plant leaves due to green chlorophyll. Although the reason for the placement of the Earth's red-edge at 0.7μm is still not fully explained, scientists have proposed it is due to the function of chlorophyll a (Björn et al. 2009) or resource limits of the available light spectrum (Kiang et al., 2007a). Another complementary signature may be present in polarization signals from the planetary surface, as a unique characteristic of Earth life is the homochirality of biological molecules. The method is particularly sensitive to detection of photosynthetic organisms, as circular dichroism (and therefore the likely circular polarization signal) is greatest within photosynthetic absorption bands (Sparks et al. 2008)

Some of these biosignatures may be affected in nature or detectability by the environmental and stellar context. For example, photosynthetic pigments with colors other than those associated with Earth chlorophyll could provide alternative signs of life in the absence of atmospheric oxygen (Tinetti et al., 2006; Kiang et al. 2007b). As the organism co-evolves with its environment, the wavelengths of the pigment absorbance features will be determined by the resulting photon and incident energy fluxes at the planetary surface, which can be modeled and predicted with knowledge of the parent star's spectrum, and the composition of the planetary atmosphere. The wavelength range of interest for these pigments likely spans 400-1100 nm. Planets around M dwarfs may exhibit surface pigment signatures in the near-infrared, where M dwarfs emit relatively more of their photons compared to the visible, and where many bacteria on Earth absorb light for anoxygenic photosynthesis. The M dwarf environment may also enhance the detectability of biogenic compounds due to the reduction in incident UV radiation, which increases the atmospheric lifetime of many species (Segura et al., 2005). For example, although the CH_4 7.7μm band is challenging to detect in a modern Earth atmosphere, it becomes significantly stronger for Earth-like planets orbiting M dwarfs, and for early Earth scenarios with higher atmospheric concentrations than for the modern Earth (Fig 2a).

Biosignatures for Alternative Metabolisms

It is likely that extrasolar terrestrial planets will have atmospheric compositions very different from that of modern Earth, even if they harbor life. An ongoing challenge in biosignature science is to learn to recognize signs of life for alternative atmospheric compositions, stellar forcings, and dominant metabolisms. Even on Earth, the global imprints of oxygenic photosynthesis – the oxidation of the atmosphere and the colonization of land surfaces by red-edge-exhibiting vegetation – took more than 2 billion years to develop, even though life existed well before these events occurred. This emphasizes the need to explore alternative signatures for a biosphere without oxygenic photosynthesis. Figure 2b) and Segura et al. (2005) show that alternative biosignature gases such as dimethyl disulfide (DMDS) and CH_3Cl could build up to detectable levels in a planetary atmosphere if the parent star's UV output is low.

Measurements and Modeling Required To Support the Themes

To characterize extrasolar terrestrial planets for all three themes we require mass, radius, density, orbital parameters, parent star age, bulk and trace atmospheric composition, and time-dependent searches for atmospheric variability or surface heterogeneities produced by continents, oceans or life. Preliminary characterization could be attempted using multi-wavelength time-resolved photometry at visible wavelengths, which could be used to search for time-dependent color changes, and the presence of ocean glint, which may be seen as a 5-10% anomaly in the lightcurve for a 50% cloud-covered planet (Williams and Gaidos, 2008). The likely diversity of terrestrial planets, coupled with multiple environmental sources for a given photometric color, will make color interpretation ambiguous, however. For similar reasons, broad-band photometry alone cannot reliably reveal the nature and abundance of gases in the planetary atmosphere.

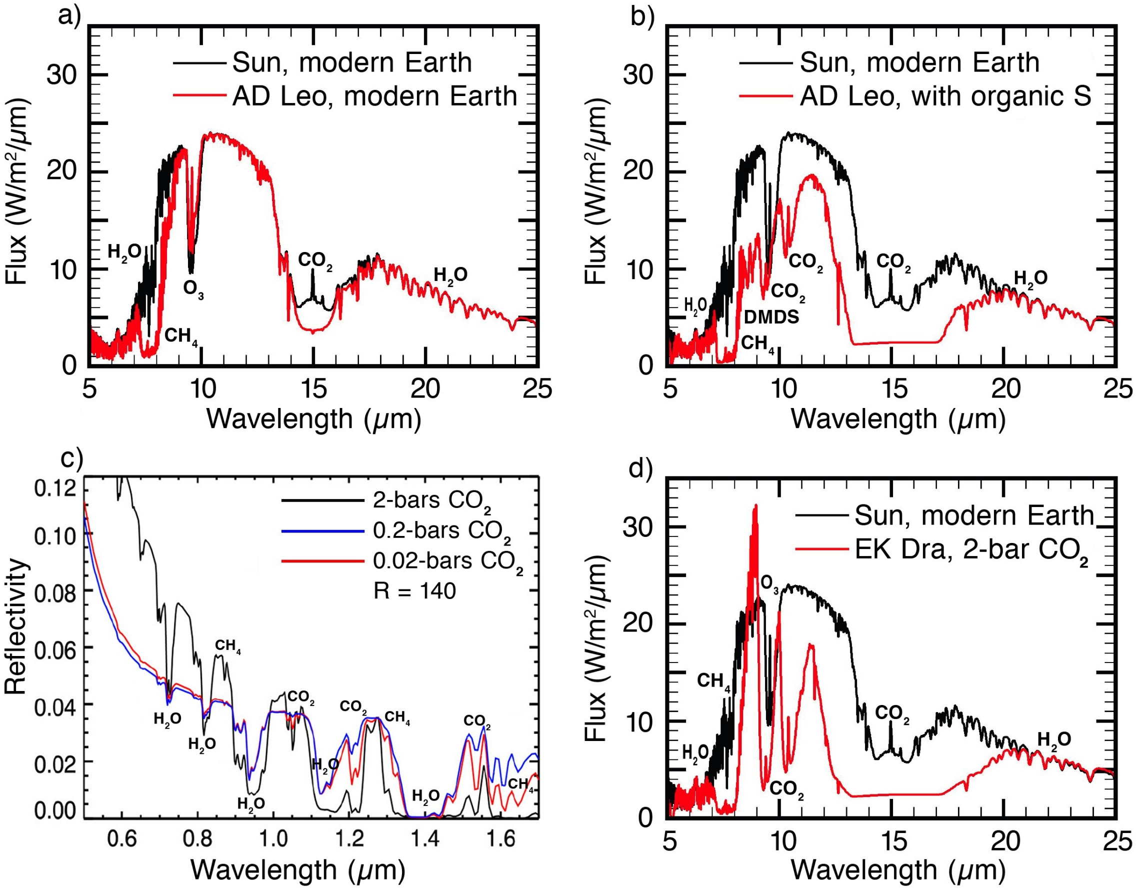

Figure 2 – Model spectra for planets unlike modern-day Earth. a) MIR spectra for an Earth-like planet around an M dwarf showing enhanced CH_4 at lower UV (Segura et al. 2005) b) MIR spectrum of an Early-Earth-like planet around AD Leo, with no O_2 (so no O_3), higher CO_2, and surface fluxes of the biogenic sulfur gases CH_3SH and DMDS (dimethyl disulfide) (Domagal-Goldman et al. (2008); c) Vis-NIR spectra for 0.02, 0.2 and 2-bar CO_2 abiotic cloudless planetary atmospheres at R ∼ 140, (Segura et al., 2007). Note the Rayleigh scattering with the denser atmosphere and the wealth of H_2O, CH_4 and CO_2 features throughout this range d) MIR spectra for an abiotic 2-bar CO_2 atmosphere with strong CO_2 absorption (Segura et al., 2007).

The best tool for assessing the composition of extrasolar planetary atmospheres and surfaces is spectroscopy. Atmospheric gases, whether planetary or biogenic, will be the most readily detectable features in the planetary spectrum. With sufficient wavelength coverage in either the UV, visible-NIR, or MIR, discrimination between multiple potential absorbers can be made even at low spectral-resolution by searching for multiple bands from the same molecule. The three likely dominant greenhouse gases in a planetary atmosphere, H_2O, CO_2, and CH_4 have strong features in both the NIR and MIR, as do alternative greenhouse gases such as SO_2 and N_2O. Desired spectral resolution in a given wavelength region will depend not only on the possible gases, but also on our likely ability to determine continuum regions, especially for planets whose a priori composition or atmospheric pressures are unknown (c.f. Fig 2c,d). The red edge vegetation signature is more challenging to detect than gases, as it is a 2-3% effect in the Earth's disk-averaged spectrum (Montanes-Rodriguez et al., 2006). The bandwidth of the vegetation red edge spans 680-761 nm, and this would need to be resolved. Instrument requirements to resolve various levels of surface cover are also discussed by Arnold et al. (2009).

To determine planetary age, constraints on stellar ages will need to be improved. Multi-wavelength observations of different spectral types at a range of ages would be valuable (e.g. Ribas et al. 2005), as would continued measurement and modeling to identifying degeneracies due to metallicity and rotation rate. Better quantification of UV fluxes from young stars, both quiescent and flaring, is vital for understanding the early evolution of planetary atmospheres.

Progress in the next decade can also be made in theoretical and laboratory efforts in understanding planetary habitability and biosignatures, which will serve to constrain instrument and telescope requirements and to interpret observations. Progress can still be made in many areas, including alternative biosignatures, the limits of photosynthesis, false positive biosignatures, dynamical and tidal evolution, the effect of clouds on our ability to characterize an environment, the limits of the habitable zone, and the effects of composition and mass on planetary volcanic activity and plate tectonics. These efforts will require multi-disciplinary collaborations between biologists, planetary scientists and astronomers.

Characterization of extrasolar terrestrial planets is challenging, but feasible, within the next decade. Improved astronomical capabilities will allow us to better understand the diversity of terrestrial planet environments, to examine the potential of these planets to support life, and to ultimately search for the global effects of life on those environments. With this astronomical capability, we will finally be able to address humanity's millenia-old questions on the plurality of Earth-like worlds, and the distribution of life in the Universe.

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