Characterizing Exoplanet Habitability

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Abstract A habitable exoplanet is a world that can maintain stable liquid water on its surface. Techniques and approaches to characterizing such worlds are essential, as performing a census of Earth-like planets that may or may not have life will inform our understanding of how frequently life originates and is sustained on worlds other than our own. Observational techniques like high contrast imaging and transit spectroscopy can reveal key indicators of habitability for exoplanets. Both polarization measurements and specular reflectance from oceans (also known as “glint”) can provide direct evidence for surface liquid water, while constraining surface pressure and temperature (from moderate resolution spectra) can indicate liquid water stability. Indirect evidence for habitability can come from a variety of sources, including observations of variability due to weather, surface mapping studies, and/or measurements of water vapor or cloud profiles that indicate condensation near a surface. Approaches to making the types of measurements that indicate habitability are diverse, and have different considerations for the required wavelength range, spectral resolution, maximum noise levels, stellar host temperature, and observing geometry.

Introduction

The emphasis on which planetary surface properties are key to determining habitability has, like many ideas in exoplanetary science, changed in time. Early work, even before the first detections of worlds around other stars, highlighted the importance of clement conditions at the planetary surface—Huang (1959) discussed the need for enough “heat” for organisms to survive, while Dole (1964) focused on a temperature range that would be suitable for humans. However, it has become widely accepted that liquid water played an essential role in the origin, develop-
ment, and maintenance of life on Earth (e.g., Brack 1993; Pohorille & Pratt 2012), and, as a result, most studies of habitability have since focused on stable surface liquid water. Rasool and de Bergh (1970), in their early description of the runaway greenhouse and the evolution of climate on the terrestrial planets of the Solar System, were amongst the first to place a strong emphasis on stable surface liquid water. Similarly, in their study of the co-evolution of Earth and life, Hart (1978) required liquid water (as well as certain atmospheric composition constraints) for life to originate.

Foundational work on habitable zones around other stars (Hart 1979; Whitmire et al 1991; Kasting et al 1993) and on the emergence of habitable worlds (Matsui and Abe 1986; Abe and Matsui 1988) strongly emphasize that habitable planets are the subset of terrestrial worlds that can have stable surface liquid water. Of course, this does not rule out the potential for sub-surface habitable environments, such as the ocean beneath Europa's icy crust (Pappalardo et al 1999; Chyba and Phillips 2001)—the emphasis on surface habitability is based in pragmatism, as discovering and characterizing any sub-surface habitable environments on exoplanets (or exomoons) will likely remain unfeasible even into the distant future.

Motivated in large part by the success of NASA's Kepler mission (Borucki et al 2010) and the ever-growing number of known potentially-habitable exoplanets, many authors and groups have sought to refine our understanding of the myriad ways a planet can (or cannot) maintain habitability (Forget and Pierrehumbert 1997; Joshi et al 1997; Stevenson 1999; Selsis et al 2007; Haqq-Misra et al 2008; von Paris et al 2010; Abe et al 2011; Pierrehumbert and Gaidos 2011; Goldblatt et al 2013; Kopparapu et al 2013; Rugheimer et al 2013; Wordsworth and Pierrehumbert 2013; Wolf and Toon 2013; Leconte et al 2013; Yang et al 2013; Shields et al 2013; Zsom et al 2013; Ramirez and Kaltenegger 2014; Luger and Barnes 2015; Way et al 2016). These studies demonstrate a relatively well-developed understanding of how a world can be habitable. The next critical step is determining which worlds are habitable—the remote characterization of habitability. Only by developing techniques for remotely assessing the likelihood that an exoplanet could have stable surface liquid water will we be able to undertake a census of Earth-like planets around our nearest stellar neighbors, thereby allowing us to test our ideas for what factors or processes enable a planet to maintain habitability.

Galileo was likely the first to consider the remote detection of surface liquid water when, in his Dialogue Concerning the Two Chief World Systems, he used the brightness of the dark portion of the lunar disk (which is illuminated by reflected light from Earth) to deduce that “seas would appear darker, and [. . . ] land brighter” when observed from a distance (Galilei 1632). Modern discussions of techniques for the remote characterization of exoplanet habitability, which are the focus of this chapter, generally fall into three categories. First, surface liquid water could be directly detected using reflection (e.g., Williams and Gaidos 2008) and/or polarization measurements (e.g., Zugger et al 2010). Second, the surface pressure and temperature of an exoplanet could be inferred from spectroscopic observations (e.g., ?), which then determines the stability of liquid water from its phase diagram. Finally, in the absence of such direct evidence for surface liquid water (or its stability), habi-
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...itability would need to be constrained using some combination of photometric and spectroscopic observations and modeling to try to best understand the planetary surface environment (e.g., Cowan et al 2009).

The direct detection of surface liquid water and the inference of surface pressure and temperature were demonstrated for Earth by Sagan et al (1993) using spatially resolved observations from a pair of flybys performed by the Galileo spacecraft. Specular reflection, which is indicative of liquids, was detected with Galileo imaging, and solid phase water absorption was identified in observations of the polar caps, thereby providing strong evidence that the surface liquid is water. Near-infrared spectral observations of thermal emission from cloud-free regions of the planet revealed surface temperatures in the range 240–290 K, and a crude spectral retrieval analysis (Drossart et al 1993) indicated an integrated atmospheric column mass $> 200 \text{ g cm}^{-2}$. For an Earth-like gravitational acceleration, this column mass corresponds to a surface pressure $> 0.2 \text{ bar}$. Given the aforementioned range of surface temperatures, the surface (even for pressures much larger than the lower limit quoted here) spans the solid-to-liquid transition regime for water, and is, thus, habitable.

Sagan et al (1993) also present multiple strong lines of evidence for Earth being inhabited. However, it is critical that approaches be developed which can be used to independently recognize both habitable as well as life-bearing planets. Employing these independent approaches, as part of a larger census of exoplanetary surface and atmospheric environments, will tell us if originating and sustaining life is common (where nearly all potentially habitable worlds are inhabited) or rare (where nearly all planets that show signs of habitability do not show signs of life). Either of these findings would tell us something profound about our place in the Universe.

From the perspective of exoplanet science, the Sagan et al (1993) Galileo results are missing a key complication—the habitability analyses all rely on spatially resolved observations. Generally, observations of exoplanets are spatially unresolved. Thus, for a true Pale Blue Dot, cloudy and clearsky, ocean and land, and warm and cold scenes would all be blended together, which significantly complicates our ability to characterize the surface environment for signs of habitability. Here, it must be emphasized that habitability is a surface phenomenon and can only be constrained if a remote observation has sensitivity to the surface (i.e., that some light at certain wavelengths in the observed spectral range comes from at/near the surface). In other words, we would have little hope of studying the surface environment of a terrestrial exoplanet that is enshrouded with completely opaque clouds.

The following sections present and synthesize studies related to the characterization of exoplanet habitability. For an earlier review on characterizing terrestrial exoplanets which includes some details on habitability, see Kaltenegger et al (2010). In our review, we begin with an overview of the key observational techniques that can be used to remotely characterize exoplanets, and highlight the sizes of signatures relevant to studying Pale Blue Dots. Following this overview, we discuss how the different observational techniques can be used to directly detect surface liquid water, to measure surface pressure and temperature, and/or to place other key constraints on the planetary environment. Whenever possible, the feasibility of detecting habit-
ability indicators is discussed. We conclude by outlining several important questions that remain unaddressed on the topic of characterizing for habitability.

**Observational Techniques**

Several observational techniques are relevant to the characterization of the atmospheres and surface environments of potentially habitable exoplanets: transit spectroscopy, high contrast imaging, and secondary eclipse spectroscopy. We briefly review these here and demonstrate the relevant signal sizes. For an overview of techniques and signature sizes for a diversity of planet types, see Cowan et al. (2015).

**Transit Spectroscopy:** In transit spectroscopy (Seager and Sasselov 2000; Brown 2001; Hubbard et al. 2001), the small fractional dimming of an unresolved exoplanet host star is measured as the planet transits the stellar disk. This quantity—the transit depth—is usually interpreted as the square of the ratio of a characteristic planetary radius ($R_p$) to the stellar radius ($R_s$), and, when measured at different wavelengths, the transit depth indicates the planetary atmospheric opacity as the world will appear larger on the stellar disk at wavelengths that correspond to larger extinction. While the overall scale of the transit depth is given by $(R_p/R_s)^2$, the contrast of spectral features will depend on the altitude difference probed within versus outside a molecular band ($\Delta z$), and is approximately,

$$\frac{2\Delta z R_p}{R_s^2} \approx 0.6 \text{ ppm} \left( \frac{T}{250 \text{ K}} \right) \left( \frac{29 \text{ g mol}^{-1}}{\mu} \right) \left( \frac{5.5 \text{ g cm}^{-3}}{\rho_p} \right) \left( \frac{R_{\odot}}{R_s} \right)^2,$$

where $T$ is a characteristic atmospheric temperature, $\mu$ is the atmospheric mean molar weight, and $\rho_p$ is the planetary bulk density. We have assumed the altitude range probed is a few pressure scale heights, and we have adopted Earth-like values for all parameters. When using this expression (and those below), input units must be the same as those for the adopted values (e.g., g cm$^{-3}$ for mass density or solar radii for the stellar radius). Using stellar radii appropriate for early, mid, and late M dwarfs, the scale of features increases to 2, 10, and 60 ppm, respectively.

**High Contrast Imaging:** In high contrast (or “direct”) imaging (Traub and Oppenheimer 2010), optical techniques are used to resolve the faint point spread function of a planetary companion from that of its bright host. Typical approaches include coronagraphy (Guyon et al. 2006; Mawet et al. 2012), external occulters or “star-shades” (Cash et al. 2007; Shaklan et al. 2010), and interferometry (Beichman et al. 1999). The relevant measure is the planet-to-star flux ratio ($F_p/F_s$), which (roughly) sets the contrast that must be achieved to accomplish imaging (although planet-star angular separation, host star apparent magnitude, exozodiacal dust brightness, and other quantities also impact the feasibility of observation). For reflected light, which would be the focus of any near-future direct imaging efforts, the flux ratio is given by $A_g \Phi(\alpha)(R_p/a)^2$, where $A_g$ is the geometric albedo, $\Phi$ is the phase function (which
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depends on the phase angle, \( \alpha \), \( a \) is the orbital distance, and where this expression omits any rotational or seasonal variability. Assuming that the insolation on potentially habitable exoplanets is roughly that of Earth \( (S_{\oplus} = 1360 \text{ W m}^{-2}) \), we have,

\[
\frac{F_p}{F_s} \approx 1 \times 10^{-10} \left( \frac{A_g}{0.2} \right) \left( \frac{\Phi}{1/\pi} \right) \left( \frac{S_p}{S_{\oplus}} \right) \left( \frac{R_p}{R_{\oplus}} \right)^2 \left( \frac{R_{\odot}}{R_s} \right)^2 \left( \frac{T_{\text{eff,}\odot}}{T_{\text{eff,}s}} \right)^4, \tag{2}
\]

where \( T_{\text{eff}} \) is a stellar effective temperature, \( S_p \) is the planetary insolation (measured relative to that of Earth), and values for an Earth-like V-band geometric albedo and phase function (at quadrature) are adopted (i.e., \( A_g \sim 0.2 \) and \( \Phi \sim 1/\pi \)). Note that it is important to distinguish between planet detection (which is driven by the planet-to-star flux ratio) and atmospheric characterization. The latter requires resolving and detecting spectral features which can be at substantially smaller planet-to-star flux ratios and, owing to the overall faintness of the planet in these features, may drive long integration times. For early, mid, and late M dwarfs, the flux ratio increases dramatically to \( 2 \times 10^{-9}, 5 \times 10^{-8}, \) and \( 4 \times 10^{-7} \), respectively. For these cooler stars, though, the small inner working angle that would be needed to resolve the planet from the star drives the need for large-diameter telescopes. Adopting \( 2\lambda/D \) as a “practical” limit to small inner working angle photometry \( \text{(Mawet et al. 2014)} \), we see that the telescope diameter required to resolve a habitable zone planet from its host is roughly,

\[
D > 4 \text{ m} \left( \frac{\lambda}{1 \text{ \mu m}} \right) \left( \frac{d}{10 \text{ pc}} \right) \left( \frac{S_p}{S_{\oplus}} \right)^{1/2} \left( \frac{R_{\oplus}}{R_s} \right)^2 \left( \frac{T_{\text{eff,}\odot}}{T_{\text{eff,}s}} \right)^2, \tag{3}
\]

where \( \lambda \) is wavelength, \( D \) is the telescope diameter, and \( d \) is the distance to the system. Returning to the early, mid, and late M dwarf cases, the lower limits on the diameter are 16, 90, and 250 m, respectively, for targets at 10 pc. Recalling that M dwarfs are more common and Sun-like stars, a more suitable characteristic distance measure is 2–5 pc, which would reduce the quoted telescope diameters by a factor of 5–2.

**Secondary Eclipse Spectroscopy:** Like transit spectroscopy, secondary eclipse spectroscopy is a differential measurement that requires the combined planetary and stellar flux prior to the planet disappearing behind its host star and comparing this to the stellar flux measured during eclipse \( \text{(Winn 2010)} \). Here, as was the case for direct imaging, the key quantity is the planet-to-star flux ratio (at full phase). Taking a mid-M dwarf as an example, in reflected light we have,

\[
\frac{F_p}{F_s} \approx 0.2 \text{ ppm} \left( \frac{A_g}{0.2} \right) \left( \frac{S_p}{S_{\oplus}} \right) \left( \frac{R_p}{R_{\oplus}} \right)^2 \left( \frac{0.2 R_{\odot}}{R_s} \right)^2 \left( \frac{2800 \text{ K}}{T_{\text{eff,}s}} \right)^4, \tag{4}
\]

which is quite small. The characteristic signature size improves at thermal wavelengths, as the planet is self-luminous at these wavelengths. Here, we have the ratio of two blackbodies, and taking the stellar spectrum to be in the Rayleigh-Jeans limit, we have,
\[ \frac{F_p}{F_s} \approx 3 \text{ ppm} \left( \frac{R_p}{R_\odot} \right)^2 \left( \frac{0.2 R_\odot}{R_s} \right)^2 \left( \frac{2800 \text{ K}}{T_{\text{eff},s}} \right) \left( \frac{\lambda}{10 \mu\text{m}} \right)^4 \left( \frac{B_\lambda(T)}{B_{10 \mu\text{m}}(250 \text{ K})} \right), \] (5)

where \( B_\lambda \) is the Planck function. As was the case for direct imaging, the depths of absorption bands can be as large as the overall signature size (for strong features) or many times smaller (for weak features).

**Direct and Indirect Approaches to Constraining Habitability**

The remote detection of habitability will require observational performances and telescope characteristics that are, potentially, significantly more strict than those outlined in the convenient expressions given above. Below, we explore just how strict these requirements will be. Our discussion focuses first on the direct detection of surface liquid water, then moves to approaches for detecting surface pressure and temperature, and, finally, explores other observational approaches to indirectly constraining habitability. In what follows, it is, of course, important to always remember that characterization can only be achieved down to the atmospheric level(s) where the continuum is set in a spectrum. For a directly-imaged Earth-twin, the visible, near-infrared, and thermal infrared wavelength ranges all have windows where surface sensitivity can be achieved, due in part to incomplete cloud coverage over Earth’s disk. However, a habitable world with, for example, thick planet-wide cloud coverage may not possess such convenient windows to the surface.

**Direct Detection of Surface Liquid Water**

Liquids, as opposed to diffusely scattering solid surfaces, have distinct polarization and scattering properties due to the process of Fresnel reflection (Griffiths 1999, p. 382). For a planar surface, the polarization signature peaks at the Brewster angle, where the polarization fraction can approach unity for a liquid with no ripples or waves. This surface will have enhanced reflectivity in the forward scattering direction where the observational angle of reflectance is equal to the solar angle of incidence (i.e., at the specular point), and this reflectivity increases towards glancing angles.

Measurements of the light polarization fraction may be an effective means to detect if an exoplanet has a surface ocean (Williams and Gaidos 2008; Stam 2008). Earthshine and spacecraft observations reveal that Earth’s polarization fraction is a function of the phase angle, peaking at values of 0.2–0.4 in the visible near quadrature (Coffeen 1979). The location of this peak is near the expected value for Rayleigh scattering, but depends on the wavelength-dependent competition between polarization from Rayleigh, cloud, haze, and ocean scattering (Zugger et al 2010). Observing at near-infrared wavelengths will minimize the Rayleigh scatter-
ing contributions, pushing the polarization fraction peak to phase angles near those expected for ocean scattering (i.e., near 100–110°), although peak polarization fractions are likely to still be < 0.2 (Stam 2008; Zugger et al 2011).

In addition to polarization, Williams and Gaidos (2008) proposed that specular reflection from an ocean—which is often called “glint”—could be used to detect surface liquid water on exoplanets. Glint would manifest itself as an increasing planetary reflectivity towards crescent phase, and such an increase has been observed in Earthshine observations (Qiu et al 2003; Pallé et al 2003) and has been used to detect liquid seas in the polar regions of Titan (Stephan et al 2010). Fig. 1 shows apparent albedo spectra of Earth at full and crescent phases, including a crescent phase spectrum where glint is removed.

Fig. 1 Apparent albedo of Earth at full phase (blue), and at crescent phase both with glint (black) and without glint (grey), from the validated model described in Robinson et al (2011). Apparent albedo is defined as the albedo a Lambert sphere (with radius equal to the planetary radius) would need to reproduce the observed brightness of the planet, and values larger than unity imply forward scattering.

An increase in reflectivity towards crescent phase is not an unambiguous detection of glint, as forward scattering from clouds, Rayleigh scattering, and geometric effects can all produce a similar behavior. Robinson et al (2010) investigated the extent of the ocean glint effect using a model that included direction-dependent Rayleigh and cloud scattering. This work showed that Rayleigh scattering false positives would be avoided by observing in the near-infrared, where the glinting Earth can be twice as bright as a non-glinting Earth. Since snow/ice reflectivity decreases
at longer wavelengths, observing in the near-infrared would also avoid the glint false positive discussed by Cowan et al. (2012a), which explains a bias towards probing the icy polar regions of a planet at crescent phases. The location of the maximum contribution from glint for Earth is near a phase angle of 150° and, for other planets, would depend on cloud cover, atmospheric thickness, and surface wind speeds. As a proof of concept, Robinson et al. (2014) were able to detect glint in unresolved LCROSS observations of Earth at a phase angle of 130°, although this study benefited from significant a priori information.

Spectral information may prove essential for distinguishing between glint and its potential false positives. Robinson (2012) noted that the unique atmospheric path traversed by a glint ray (i.e., two straight-line passes through the atmosphere with a single scattering event at the ocean surface) would imply that a significant portion of the crescent phase spectrum of Earth should resemble a solar spectrum modulated by Rayleigh scattering and gas absorption opacity. Fig. 2 demonstrates this signature. Here, a full phase spectrum of Earth is corrected to crescent phase using a Lambert phase function, and is then subtracted from a crescent phase spectrum of Earth. This difference spectrum, in essence, represents the forward scattering excess (due primarily to clouds and glint) at crescent phase. In wavelength ranges with relatively little gas absorption and, thus, high surface sensitivity, the difference spectrum can be well reproduced by a solar spectrum weighted by a term going as $\exp\left(\frac{b}{\lambda^4}\right)$ to account for Rayleigh scattering.

Detecting glint or ocean polarization signatures requires, first and foremost, surface sensitivity and a favorable orbital inclination for the target so that the appropriate phase angles can be accessed. Polarization fraction peaks span roughly 45° of phase angle, implying a minimum required inclination of 20–30° (where an inclination of 90° is edge-on). Additionally, by error propagation, measuring a polarization fraction of $f$ (which is the difference between the perpendicular and parallel polarized fluxes divided by the total flux) to a given signal-to-noise ratio (SNR; given by $f/\sigma_f$) would require that the total flux measurement be improved by a factor of $\sqrt{2}/f$, implying a total flux measurement SNR (i.e., $F/\sigma_F$) of roughly 20 is needed to detect $f \sim 0.2$ at SNR = 3. For the glint signature, which occurs at more extreme phases, detection would require a minimum inclination of about 60°. For such favorable inclinations, resolving an Earth twin at $2\alpha$ from a Sun-like host at 10 pc with a coronagraph would require an 8 meter diameter telescope (taking $\alpha = 150°$ and $\lambda = 1 \mu m$), or a starshade capable of providing an inner working angle of 50 mas. For a Sun-like host at 5 pc, these requirements drop to a 4 meter diameter telescope or a starshade with a 100 mas inner working angle. Notably, both the polarization and glint measurements can be accomplished with broadband observations that avoid strong near-infrared molecular features, which helps to drive down requisite integration times.
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Fig. 2. Spectral signs of glint in phase-dependent observations of Earth. A full phase spectrum of Earth is corrected to crescent phase using a Lambert phase function (dark blue) and subtracted from a crescent phase spectrum of Earth (black) to produce a difference spectrum (grey). The result is well reproduced in window regions by a model that represents a solar spectrum that experiences Rayleigh scattering opacity (light blue) as it passes twice through the atmosphere and scatters once at the surface.

**Surface Pressure and Temperature**

Numerous indicators impart information about pressure and temperature on spectra, although the scale of these signatures can sometimes be quite small. The Rayleigh scattering optical depth is sensitive to the column abundances of primary atmospheric constituents, molecular lines (and bands) are broadened by pressure and thermal effects, and infrared spectra directly indicate the atmospheric and, possibly, surface thermal state. Thus, depending on the wavelength range and observational approach, it is possible to use spectra to make inferences about the pressure and temperature at the surface of an exoplanet, thereby constraining habitability.

For reflected light observations, direct pressure and temperature information will come primarily from the Rayleigh scattering slope and from the widths of molecular bands. Figure 3 shows reflectivity spectra of cloud-free worlds with different atmospheric temperatures and pressures where water vapor is the only absorber. The water vapor column mass is Earth-like and held fixed, so that variations are only due to pressure and temperature effects. The influence of atmospheric temperature is extremely small. On the other hand, pressure has a strong influence on band widths and depths, as well as the extent of the Rayleigh scattering slope. Raman scatter-
ing can also indicate atmospheric column density (and, thus, pressure, if the surface gravity is known), is most apparent for surface pressures well in excess of 1 bar, and requires measurements at ultraviolet wavelengths (Oklopčić et al. 2016).

![Reflectivity spectra demonstrating pressure and temperature sensitivities. All cases are clearsky and have the same mass and radius as Earth. Water vapor is the only absorbing gas, and the column mass of this species is constant and Earth-like across all spectra. The background gas is molecular nitrogen. Temperature effects are shown in grey colors (spanning 100 K) and pressure effects are shown in blue colors (spanning two orders of magnitude).](image)

Our ability to extract pressure information from reflected light spectra will be complicated by uncertainties in planetary mass, planetary radius, the mass(es) of the primary atmospheric constituent(s), and clouds. The Rayleigh scattering optical depth is ultimately sensitive to column number density, so that pressure, gravity, and atmospheric mean molecular weight are degenerate. Estimates of surface gravity could be dramatically improved using radial velocity (or astrometric measurements, or through measuring transit timing variations if the world happens to be in a multi-planet transiting configuration), although, for Earth-like planets around early-type stars, the precision required for this measurement will be challenging to achieve (Lovis and Fischer 2010). Finally, pressure broadened line half widths are dependent on the composition of the background atmosphere (e.g., Gamache et al. 1997), with the largest effects being due to self-broadening (Hedges and Madhusudhan 2016).

Collision induced absorption features and dimer features—both of which are quite sensitive to background pressure—have been proposed as key indicators of pressure on exoplanets (Misra et al. 2014a). Such features have been detected in
transmission spectra of Earth’s atmosphere (Pallé et al. 2009), and in near-infrared spectra of the Pale Blue Dot (Schwieterman et al. 2015). In general, collision induced absorption and dimer features are usually stronger in reflected light and thermal emission spectra, since these techniques tend to probe deeper into atmospheres than transit spectra. Strong molecular nitrogen pressure induced absorption is limited to a feature near 4.3 \( \mu m \) (Schwieterman et al. 2015), key molecular oxygen features are at 1.06, 1.27, and 7 \( \mu m \) (Misra et al. 2014a), carbon dioxide has a broad feature near 7 \( \mu m \) (Baranov et al. 2004), and molecular hydrogen (which has been proposed as a potential major atmospheric constituent for, e.g., super-Earths) has numerous features spanning the visible, near-infrared, and thermal infrared (Frommhold et al. 2010; Abel et al. 2011).

Transit spectra, through their sensitivity to the atmospheric pressure scale height \((RT/\mu g\), where \(R\) is the universal gas constant\), contain additional information about temperature (Lecavelier Des Etangs et al. 2008), atmospheric mean molecular weight (Benneke and Seager 2012), and, potentially, gravitational acceleration (or mass; de Wit and Seager 2013) (although see Batalha et al. 2017). However, while a transit spectrum of an Earth twin would be rich with spectral features (Kaltenegger and Traub 2009), there are a variety of processes that minimize (or prevent) sensitivity to the surface environment. Fundamental amongst these processes is atmospheric refraction, where rays passing through deeper regions of a planetary atmosphere can experience enough refraction to bend them off the stellar disk (Bétrémieux and Kaltenegger 2014; Misra et al. 2014b). For Earth-like planets around Sun-like stars, refraction prevents sensitivity to the troposphere—although a small amount of the light that passes through the planet’s atmosphere near transit ingress and egress can follow paths that pass near the surface (Misra et al. 2014b).

In addition to refraction, extinction can also limit surface sensitivity in transit spectroscopy of Earth-like planets. Here, long slant pathlengths associated with the transit geometry cause spectral regions with only a small amount of vertical optical depth to become opaque. This issue is especially true for clouds and hazes (Fortney 2005), which tend to have optical depths that vary slowly in wavelength, and can thus block observations of the deep atmosphere over wide spectral ranges (e.g., Kreidberg et al. 2014; Knutson et al. 2014; Robinson et al. 2014). Aerosol extinction in transit spectra would be significant for a hazy early Earth (Arney et al. 2016), and even modern Earth, which is generally thought to have “patchy” clouds, is >70% cloud-covered when thin, high-altitude cirrus clouds are considered (Stubenrauch et al. 2013). Fig. 4 shows transit spectra of Earths around different host star types, and includes the effects of realistic clouds and refraction.

Achieving the types of transit observations outlined in this section is made difficult by detector noise and systematics, as well as clouds. Greene et al. (2016) showed that the James Webb Space Telescope (JWST), with an adopted set of instrument systematic noise floors based on analogies to previously-flown Hubble and Spitzer instruments, is unlikely to be able to place strong constraints on the atmospheric
Fig. 4  Transit spectra of an Earth twin around a Sun-like, M0 dwarf, and M5 dwarf host. Clearsky cases are in grey, blue curves show the addition of realistic clouds, and black curves contain both clouds and refraction. From a transit spectra model described in Robinson (2017).
properties of a warm (500 K) super-Earth planet with a steam atmospheres transiting an M0 dwarf using transit or secondary eclipse spectroscopy. By pushing to a mid-M dwarf host, Benneke and Seager (2012) concluded that JWST could place constraints on the surface pressure of a similarly warm super-Earth planet with an atmosphere dominated by molecular nitrogen. The Benneke and Seager (2012) results did not address clouds, refraction, detector systematics, or cooler (Earth-like) atmospheres, all of which will make detections of surface pressure more difficult. Most promisingly, de Wit and Seager (2013) found that JWST could constrain pressures and temperatures for a cloud-free Earth-like planet orbiting a late-M dwarf using 200 hr of in-transit observation time, although potential degeneracies may exist (Batalha et al 2017).

Few studies exist that address the information content (especially with regard to surface pressure and temperature) of directly observed Earth-like exoplanets. Using retrieval techniques to fit simulated observations of a cloud-free Earth in the thermal infrared, von Paris et al (2013) showed that surface temperatures and pressures for Earth-like planets could be constrained to within the habitable range with spectral resolutions (R = λ / ∆λ) greater than roughly 10 and SNRs per spectral element greater than roughly 10, although these estimates are likely optimistic given the omission of clouds. While no similar studies exist for Earth-like planets in reflected light, it should be noted that pressures of cloud decks in giant planets are not well constrained by modest resolution (R = 70) visible wavelength spectra, even at SNRs of 20 (Lupu et al 2016), and this problem is exacerbated when the planetary phase angle and size are unknown (Nayak et al 2016). Extending the observed wavelength range and including pressure-dependent opacities may help to better constrain pressures.

**Other Habitability Indicators**

A variety of observations, while not direct confirmations of habitability, could also be used as evidence for liquid water at/near the surface of an exoplanet. Within this area, the topic that has seen the most study is that of photometric variability. At visible wavelengths, contrast between Earth’s reflective clouds and its surface—which is absorptive due to the large ocean coverage fraction—makes our planet the most variable in the Solar System (Ford et al 2001; Oakley & Cash 2009), with peak-to-trough diurnal variations typically of order 20% (Livengood et al 2011).

Rotationally resolved, visible wavelength observations of the Pale Blue Dot could be used to produce surface feature maps, including continent and ocean features that may indicate long term habitability (Cowan et al 2009; Fujii et al 2011; Cowan et al 2011). Lightcurves resolved over longer timescales could indicate variability due to weather or seasons. Thermal infrared lightcurves could also reveal variability due to weather, rotation, or seasons (Hearty et al 2009; Robinson 2011; Gómez-Leal et al 2012; Cowan et al 2012). Observations of variability due to weather for a distant Earth-like planet, coupled with information about the planetary
orbit (or insolation), would likely argue for atmospheric water vapor condensation, although the condensate phase (liquid or solid) and whether or not the aerosols reach a surface in a liquid state would be difficult to discern. Confirmation, or detection, of the presence of liquid droplets, as well as their composition, could come from reflectance and polarization measurements at phase angles corresponding to maximum scattering from the primary rainbow of the droplets (Bailey 2007), although accessing these phase angles requires orbital inclinations like those needed for glint measurements.

Detecting other signs of water vapor condensation, especially near an exoplanetary surface, would make for stronger indications of habitability. Fujii et al (2013) used rotationally resolved spectra of the Pale Blue Dot to detect differences in the spatial distribution of water vapor and molecular oxygen in Earth’s atmosphere. Since molecular oxygen is well-mixed, this detection argues for a non-uniform vertical and horizontal distribution of water vapor, where the most likely interpretation for a potentially habitable exoplanet would be exchange between the gas and liquid/solid phase. More recently, Robinson and Marley (2016) noted that retrieval of a water vapor mixing ratio profile that is larger near an exoplanetary surface, or the retrieval of a condensate cloud layer located near the surface of a potentially habitable exoplanet, would argue for stable surface liquid or solid water.

Mapping of Pale Blue Dots is made difficult by the requisite SNRs, and, potentially, the need for simultaneous photometry in multiple bands (although these bands can be wide, which helps to increase the signal from the planet). Cowan and Strait (2013) use diurnal lightcurves at a SNR of 100 to map the Pale Blue Dot without prior information for surface or cloud spectra, although simply detecting changing cloud patterns may only require SNRs larger than roughly 20–30. Fig. 5 shows how the integration time required for V band photometry depends on distance to the system and telescope diameter. If SNRs of 100 are required within 2–4 hr (for rotational resolution), then mapping will be limited to only very nearby targets. However, if mapping can be accomplished with lower SNRs, then targets out to much larger distances can be accessed, even with modest-sized telescopes. Finally, note that retrieving water vapor or cloud profiles from reflected light observations will also require high-SNR observations, at least if the jovian cloud retrievals mentioned in the previous section are indicative.

**Outstanding Challenges**

While a variety of techniques and observables relevant to characterizing habitability have been proposed, key questions still remain about the feasibility and utility of these different methods. Regarding the direct detection of surface liquid water, requisite integration times for realistic observing scenarios have yet to be explored. Performing these observations in the near-infrared (where stars are fainter) may prove costly, and noise from observing near the inner working angle (for glint) or from polarized light from exozodiacal dust will both introduce complications. Similarly,
Fig. 5 Contours of integration time required to achieve a SNR of 100 (grey) and 30 (blue) for Earth twins in V band as a function of telescope diameter and distance to the planetary system. Only noise from stellar leakage (at a raw contrast of $10^{-10}$), Solar System zodiacal light, and exozodiacal light (at the level of three exozodis) are considered. Models assume a Sun-like host, and relevant expressions are given in Robinson et al. (2016). Achieving a SNR of 100 would be strongly limited by systematic noise floors.

Table 1 Key Habitability Observables and Constraints for Earth Twins.

| Observable | Technique       | Wavelength | Noise Req. | Add'l Considerations |
|------------|-----------------|-------------|------------|----------------------|
| glint      | direct imaging  | 0.7–2.5 μm  | $\text{SNR} \gtrsim 3$ | broadband; $i \gtrsim 60^\circ$ |
| polarization | direct imaging | 0.7–2.5 μm  | $\text{SNR} \gtrsim 20$ | broadband; $i \gtrsim 20$–$30^\circ$ |
| transit    | direct imaging  | 0.4–30 μm   | $\lesssim 10$–$50$ ppm | $R \gtrsim 100$; mid/late-M dwarf |
| surface $p$ & $T$ | direct imaging | 0.4–2.5 μm  | $\text{SNR} \gtrsim 20$ (?) | $R \gtrsim 100$; no $T$ constraint |
| direct imaging | 4–30 μm        | $\text{SNR} \gtrsim 5$–$10$ | $R \gtrsim 10$ |
| weather/mapping | direct imaging | 0.4–1 μm    | $\text{SNR} \gtrsim 30$–$100$ | broadband |
| $\text{H}_2\text{O}$/cloud profiles | direct imaging | 0.4–2.5 μm  | $\text{SNR} \gtrsim 20$ (?) | $R \gtrsim 100$ |
SNRs (which dictate integration times) required for retrieving pressure, temperature, and/or water vapor and cloud profiles from reflection, emission, and/or transmission spectra of realistic Pale Blue Dots also remain largely unexplored. Finally, future work on variability should focus on the wavelength range, timing, and minimum required SNRs to do mapping. Table 1 presents an overview of the current understanding of the observing requirements for the different approaches to detecting or constraining habitability.

Once observational feasibility has been addressed, a more holistic discussion of characterizing for habitability should emerge. This will be especially true for high contrast imaging. Here, repeat observations may be required to confirm the planetary nature of a target and to constrain the orbit (and, thus, insolation) of a confirmed planet. It is unclear if certain observational tests for habitability should be worked into the confirmation and orbit determination sequence. Also, following this sequence, open questions remain regarding the order in which different observations (e.g., glint, polarization, moderate resolution spectroscopy) should take place. Such questions can only be settled by weighing the information supplied by these different observations with the time required to achieve them.

Conclusions

Detecting or constraining the habitability of a distant exoplanet will be a challenging and critical step towards understanding the frequency of the origin of life on other worlds, and would also inform our understanding of the climate and evolution of terrestrial planets. Transit spectroscopy, secondary eclipse observations, and high contrast imaging all have the potential to reveal key planetary properties related to habitability, and these techniques each have their own assets and challenges. Reflected light observations can directly reveal surface liquid water, either through polarization or glint measurements. Constraints on surface pressure are possible with most observational techniques (depending on wavelength coverage), but surface temperatures (which, when combined with a surface pressure measurement, can demonstrate habitability) will prove difficult to measure in reflected light. Detecting water vapor condensation at/near a surface is also feasible, either through spectral retrieval of gas mixing ratio or condensate profiles, or through mapping using time resolved photometric measurements. In the end, though, it could prove that no unambiguous “smoking gun” exists for detecting stable surface liquid water, so that actual constraints on habitability may come from multiple lines of evidence using a variety of approaches brought to bear on a distant Pale Blue Dot.

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