Astro2020 Science White Paper

The Mid-Infrared Search for Biosignatures on Temperate M-Dwarf Planets

Thematic Areas: ☑ Planetary Systems ☐ Star and Planet Formation
☐ Formation and Evolution of Compact Objects ☐ Cosmology and Fundamental Physics
☐ Stars and Stellar Evolution ☐ Resolved Stellar Populations and their Environments
☐ Galaxy Evolution ☐ Multi-Messenger Astronomy and Astrophysics

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Abstract (optional): One of the most promising paths towards the search for life on other worlds is via transmission spectroscopy of rocky planets in the habitable zones of nearby M-dwarf stars. In this science white paper, we present the importance of transiting planets in understanding habitability, and how the mid-infrared provides a unique spectroscopic window to the most prominent signatures of life. We further describe how studying rocky M-dwarf planets presents an opportunity to understand how life might evolve in an environment not like our own. Ultimately, we recommend the development of a large space-based infrared telescope with a custom-designed time-series spectrophotometer that can target bright objects with high-precision (low noise floor) detectors and provide simultaneous broad-wavelength coverage. Such a mission would draw from an observationally-complete sample of targets with previously-known planetary radii and bulk densities, and would build on proven observational techniques that have characterized the atmospheres of nearly 100 transiting exoplanets.

1 Introduction

The past 30 years of exoplanet science have shown us that planets are common around nearby stars. Now, and in the coming years, we would like to characterize these worlds. What are the atmospheres of temperate rocky planets like? Do these planets have life? Currently, the climate and compositional diversity of potentially habitable terrestrial worlds is not known, and it is likely that our imaginations and models will fail to predict the broad range of solutions. Therefore, we must rely on observations to drive our understanding. In principle, these observations could be made at a range of wavelengths, including optical or near-infrared light seen in reflection, and thermal infrared seen in emission. They could be conducted for potentially habitable worlds across a range of stellar masses, from Sun-like stars to M dwarfs.

In this white paper we outline a path towards understanding the atmospheres and habitability of transiting terrestrial planets in the habitable zone (HZ) of M dwarfs. What sets this path apart is that it builds on a sample of planetary targets that should be complete within the next few years, and it uses observational techniques already demonstrated and proven for larger planets. We recommend that the key to enabling this path is a large space-based telescope that is custom-designed for high-precision time-series spectrophotometry over mid-infrared wavelengths.

2 Transiting Planets are Important for Understanding Habitability

Transiting planets have driven the growth of exoplanetary science from planetary *discovery* to planetary *characterization*. Imagine how little we would know about exoplanetary atmospheres today without transiting planets. Characterizing the atmospheres of transiting planets is built on precisely measured quantities. Transiting planets targeted for observations have measured radii. With followup radial velocity observations, they have a measured mass, surface gravity, and bulk density, which yields the planet's bulk composition. Within the next $\sim$10 years, TESS, SPECULOOS, and other such missions should discover every Earth-size planet transiting the nearest ($<$15 pc) mid-to-late M dwarfs in the night sky. All such planets in the HZs of their parent stars will have their masses determined by red-optical and near-IR precision spectrographs coming online in the next decade. Thus, a mission that would characterize these planets and search for biosignatures would not have to find or characterize the bulk densities of these targets a priori: no planet-search mission phase would be required. These advantages would flow down to benefit an exoplanet characterization mission with more time spent on in-depth atmospheric studies.

Transmission and emission spectroscopy are proven observational techniques that have delivered a huge array of "firsts" in the study of exoplanet atmospheres. These techniques have already been used across a wide range of planet masses, from gas giants around Sun-like stars to terrestrial planets orbiting M dwarfs. Emission spectroscopy, in particular, can simultaneously deliver an atmosphere's chemical abundances and temperature structure. Thus far, exoplanet scientists have cleverly utilized instruments never designed for precision spectrophotometry to deliver the first atmospheric measurements on a surprisingly large sample of transiting exoplanets. However, in order to fully take advantage of these techniques in characterizing potentially habitable planets, future observers will need instruments custom-designed for high-precision observations.

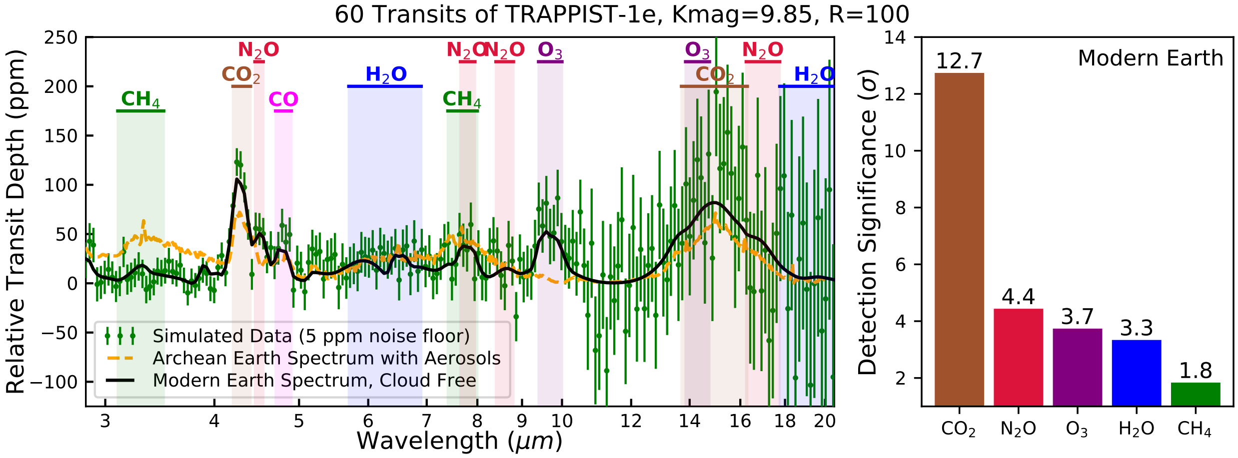

Figure 1: **A mid-infrared mission expressly designed with simultaneous, broad-wavelength coverage and a low (~5 ppm) noise floor would be primed to detect key bio-indicator and biosignature gases in the atmospheres of terrestrial planets in the habitable zones of M dwarfs.** These model transmission spectra for a TRAPPIST-1e-like planet with Archean-Earth and modern-Earth-like compositions (60 transits, Kmag = 9.85, R = 100, JWST-size mirror) highlight the abundance and diversity of molecules in the mid-IR (left) and their detection significances (right). Such a mission would be sensitive to the biosignature pair O_3+N_2O at $> 3.6\sigma$ in a modern Earth atmosphere. Spectra courtesy of M. R. Line and T. J. Fauchez.

3 The Mid-IR Provides An Ideal Window to Biosignatures

Mid-infrared wavelengths provide a unique spectroscopic window to assess habitability, as they are sensitive to the strongest transitions of most molecules (see Figure 1), including:

- The bio-indicator gases H_2O and CO_2;
- The biosignature pairs O_3+N_2O and O_3+CH_4;
- Collision-induced absorption from O_2–O_2 and N_2–N_2; and
- Other potentially abundant atmospheric constituents (e.g., NH_3, CO, hydrocarbons, etc.).

A telescope with broad mid-IR wavelength coverage would provide the context that comes from the detection of multiple molecular bands. This, in turn, would prove critical in definitively measuring atmospheric abundances, and ruling out abiotic scenarios (e.g. Wordsworth & Pierrehumbert 2014, Luger & Barnes 2015, Domagal-Goldman et al. 2014. Broad wavelength coverage also readily allows for the detection of the unexpected. Exoplanet science to date has shown us that nature's imagination is richer than ours, and a broad-wavelength, mid-IR instrument would allow for these unexpected discoveries. The mid-IR opportunity also relates to the planet's thermal emission. Wien's Law (λ_{max} in $\mu m = 2898/T$) shows that temperate planets are brightest and the signal-to-noise is highest between 7 – 15 μm.

4 M Dwarfs are Compelling Planet-Hosting Stars

M dwarfs are ideal parent stars for characterizing small, potentially habitable planets for a number of reasons. First, thanks to *Kepler*, the frequency of rocky planets in the HZ around M dwarfs is known to be high ($43^{+14}_{-9}\%$, Dressing & Charbonneau 2015). Second, since the HZs around M dwarfs are much closer to their stars than Sun-like stars, the probability of detecting temperate planets in transit is higher—the transit probability for close-in planets is R_s/a, where R_s is the radius of the star and a is the orbital semi-major axis (Winn, 2010). Third, transits are more frequent around M dwarfs due to the planets' short orbital periods. Fourth, Earth-size planets orbiting M dwarfs also feature comparatively large transit depths ($\sim 1\%$) relative to similarly-sized planets orbiting Solar-type stars ($\sim 0.01\%$). Lastly, terrestrial planets in the HZs of M dwarfs are the only potentially-habitable planets whose masses can precisely measured using radial velocity observations with current or near-term facilities.

M dwarfs also have unique features that make assessing the habitability of their planetary systems distinct from that of Sun-like stars. This is both a challenge and an opportunity. It is a challenge in that the formation, evolution, and current environment of the planets may strongly differ from that of the Earth, where our intuition for habitability has necessarily developed. It is a fantastic opportunity, however, because we have the ability to understand how a range of different physical processes may give rise to planetary atmospheres that may or may not support life.

First, since the habitable zones of M-dwarf planets are much closer to the star than our Sun, this would lead to strong tidal effects, including the likelihood of tidal circularization. In some cases, this can result in synchronous rotation, and thus these planets could have permanent day and night sides (Kasting et al. 1993; Wordsworth, 2015). Modern climate models for such worlds suggest this is not a barrier to habitability, as previous concerns of atmospheric freeze-out on the night side would only occur for tenuous atmospheres (Joshi et al. 1997; Joshi, 2003; Yang et al. 2013; Kopparapu et al. 2016; Haqq-Misra et al. 2018).

Second, HZ planets orbiting M dwarfs experience higher XUV fluxes and stellar winds relative to those orbiting Sun-like stars. This could lead to increased atmospheric mass loss or surface sterilization, especially at young stellar ages when XUV fluxes are stronger (e.g., Tian, 2009; France et al. 2013; Loyd et al. 2016; Dong, 2017). However, the masses and bulk densities of most TRAPPIST-1 planets are consistent with having volatile-rich atmospheres (Grimm et al. 2018). Additionally, life on Earth can survive in extreme environments (extremophiles) and, during periods of high XUV flux, life can survive under water or below the surface.

Third, M dwarfs and Sun-like stars have different evolution histories at young ages. While the Sun was $\sim$30% fainter at the time of Earth's formation, M dwarfs are brightest during the planet formation era. Thus, similar to how the faint young Sun paradox cannot explain liquid water early in Earth's history, M dwarf planets face the potential for a desiccated environment devoid of volatiles and/or significant oxidation of the planetary crust and mantle (Luger & Barnes, 2015; Tian & Ida, 2015). However, similar to Earth, water on M dwarf planets could be replenished through cometary material. Overall, only through characterizing these exotic worlds can we put our own planet in context to answer the question: how unique is the pathway to habitability?

4.1 Assessing the Observational Impact of Stellar Activity

Stellar activity can affect a planet's measured spectrophotometic transit signal and, therefore, a planet's retrieved physical properties (e.g., Pont et al. 2008, Czesla et al. 2009, Berta et al. 2011, Désert et al. 2011, Fraine et al. 2014, Oshagh et al. 2014, Zellem et al. 2015, Rackham et al. 2018, Morris et al. 2018). While M-dwarf stars can be comparatively more active than Sun-like stars, stellar activity has a larger impact on the observed transit spectrum in the visible than in the infrared (e.g., Knutson et al. 2012; McCullough et al. 2014; Zellem et al. 2017; Rackham et al. 2017) and studies have shown activity to have a negligible impact on the observed infrared spectrum (e.g., Fraine et al. 2013; Kreidberg et al. 2014; Zellem et al. 2017; Morris et al. 2018; Bruno et al. 2018). Similarly, we do not anticipate stellar granulation to be a significant source of error ($\lesssim$5 ppm) as recent studies that attempt to model the planet transit across stellar surface granules at different wavelengths confirm this estimate (Chiavassa et al. 2017; Sarkar et al. 2018).

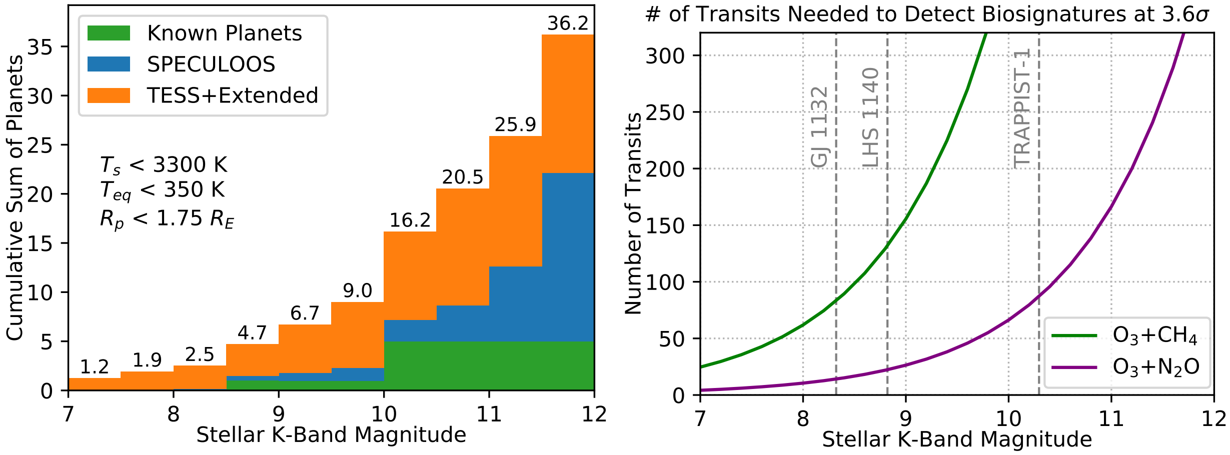

Figure 2: **Left:** Cumulative number of known and predicted temperate, terrestrial planets transiting mid-to-late M dwarfs, derived from estimated yields from TESS' primary (2-year) and extended (∼2-year) mission (Barclay et al. 2018; priv. comm.) and SPECULOOS' primary survey (Delrez et al. 2018) **Right:** Number of transits needed to detect biosignature pairs O_3+N_2O and O_3+CH_4 at 3.6σ confidence, assuming a TRAPPIST-1e-like planet with a modern-Earth composition orbiting an M8 star.

Therefore, based on these studies, we anticipate that stellar activity would not significantly impact the performance of near- to mid-IR transit or eclipse observations.

For the rare cases of an exceptionally active and bright host star featuring an exoplanet with a large transit depth, epoch-to-epoch planetary changes due to stellar variability can be corrected with high-precision, out-of-transit or in-eclipse measurements, which probe the light of the star alone (Zellem et al. 2017). In addition, persistent, non-variable, unocculted activity can be identified and corrected for by comparing the host star's spectrum to stellar models (e.g., PHOENIX spectra; Husser et al. 2013; Rackham et al. 2017, 2018; Wakeford et al. 2019).

4.2 Predicted Yields of M-Dwarf Planets

NASA's TESS mission is currently conducting an all-sky survey that will potentially discover 10,000+ new transiting exoplanets, ∼13 of which are predicted to be temperate, terrestrial worlds transiting M dwarfs that are suitably bright for atmospheric characterization (Barclay et al. 2018; priv. comm.). Combined with currently-known planets and discovery estimates from the SPECULOOS survey (Delrez et al. 2018), there will be ∼26 potentially-habitable planets transiting nearby, bright ($K < 11.5$) M-dwarf stars (see Figure 2, left panel).

4.3 Adopting a Layer-Cake Observing Strategy

In order to prioritize targets to survey, we would adopt a three-tiered "layered cake" strategy inspired by ESA's ARIEL observing scheme (ARIEL Assessment Study Report, ESA/SCI(2017)2[1]). Observations of giant exoplanet atmospheres have shown that aerosols (clouds or hazes) can obscure absorption features of the major atmospheric gases, thus limiting atmospheric characterization (e.g., Iyer et al. 2016, Sing et al. 2016; Wakeford et al. 2019). Therefore, the first tier of this proposed exoplanet survey would identify the planets with the clearest atmospheres for further study via spectral modulation. The next tier would leverage dayside emission spectra to measure the apparent surface temperatures of those planets with clear atmospheres. This tier would find temperate planets (here defined as the temperature where liquid water can exist on a planet's

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[1] http://sci.esa.int/cosmic-vision/59109-ariel-assessment-study-report-yellow-book/

surface) and eliminate those that are too hot or too cold. The last tier would feature additional transits to build up the SNR necessary to detect biosignatures on the previously-identified clear and temperate planets. The right panel of Figure 2 estimates how many transits would be needed (as a function of stellar magnitude) to detect biosignatures on a TRAPPIST-1e-like planet with a modern-Earth composition using a JWST-sized mid-IR telescope.

Thus, while this observational strategy would be designed to measure biosignatures, it would also provide a study of the aerosol statistics/frequency on a sizable sample ($\sim$20 planets) as well as the frequency of potentially-habitable planets by identifying those that are too hot, like Venus, or those have tenuous atmospheres, like Mars.

5 Future facilities

There are numerous facilities on the horizon that will aim to characterize temperate M-dwarf planets. JWST will certainly perform a reconnaissance of the most promising rocky exoplanets transiting mid-to-late M-dwarfs, primarily in transmission at infrared wavelengths using the NIRISS, NIRSPEC, NIRCAM, and MIRI instruments (e.g., Morley et al. 2017, Batalha et al. 2018). However, it is unclear if JWST+MIRI/LRS (5–12 μm) will have the necessary precision to detect biosignature gases such as $\mathrm{O_3}$ and $\mathrm{CH_4}$. Beyond 12 μm, MIRI is currently limited to broadband photometry for time-series observations. From the ground, extremely large telescopes (ELTs) will search for $\mathrm{O_2}$ using high-resolution spectrographs (Snellen et al. 2013, Rodler et al. 2014), but thermal background noise limits this approach at wavelengths greater than $\sim$5 microns (Snellen et al. 2015). Consequently, efforts to characterize M-dwarf planets both from the ground and space will be highly complementary.

6 Recommendations

To perform a deep reconnaissance of potentially-habitable M-dwarf planets, we recommend the following:

- A telescope with a large field of regard to maximize the number of available transits for any given system during its mission lifetime;
- An instrument with simultaneous wavelength coverage of at least 3.0–20 μm and a spectral resolving power of at least 50 to uniquely and efficiently identify multiple spectroscopic features from a wide range of potential biosignatures; and
- Detectors designed specifically for high-precision time-series observations of bright objects with validated noise floors of $\lesssim$5 ppm.

Upon implementing these recommendations, we could determine the atmospheric compositions and thermal structures of dozens of potentially habitable planets, thus opening the door for comparative exoplanetology of rocky worlds. We find that, assuming a realistic atmospheric composition for an Earth-size planet orbiting an M8 dwarf star, a JWST-size telescope with broad simultaneous wavelength coverage of at least 3–20 microns, and detectors with $\lesssim$5 ppm noise floors, we would be capable of detecting H_2O, CO_2, O_3, and N_2O at $> 3\sigma$ statistical significance (Figure 1, right panel). At slightly higher concentrations, CH_4 could also be detected. When found together in a terrestrial atmosphere, O_3+N_2O or O_3+CH_4 are currently two of the best-known biosignature pairs (Schwieterman et al 2018) and, importantly, would help rule out abiotic scenarios (e.g. Wordsworth & Pierrehumbert 2014, Luger & Barnes 2015, Domagal-Goldman et al. 2014). Our results support the continued exploration of transiting exoplanet missions as a means to characterize terrestrial exoplanet atmospheres in the search for life.

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