Characterizing Potentially Habitable Planets orbiting M-dwarfs with Thermal Phase Curves

A white paper submitted in response to the NAS call on
Exoplanet Science Strategy

Tiffany Kataria - Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Dr, Pasadena 91109; tiffany.kataria@jpl.nasa.gov

Kevin B. Stevenson – Space Telescope Science Institute
Jonathan J. Fortney – University of California at Santa Cruz
Ravi Kopparapu – NASA Goddard Space Flight Center
Eric T. Wolf – University of Colorado, Boulder
Robert T. Zellem – Jet Propulsion Laboratory, California Institute of Technology
Richard K. Barry – NASA Goddard Space Flight Center
Zachory K. Berta-Thompson – University of Colorado, Boulder
Giovanni Bruno – Space Telescope Science Institute
Nicolas B. Cowan – McGill University
Pablo A. Cuartas-Restrepo – FACom-FCEN, Universidad de Antioquia, Medellín, Colombia
Chuanfei Dong – Princeton University
Tom Greene – NASA Ames Research Center
William C. Danchi – NASA Goddard Space Flight Center
Jonathan Fraine – Space Telescope Science Institute
Eric Gaidos – University of Hawaii at Manoa
Peter Gao – University of California, Berkeley
Mercedes Lopez-Morales – Harvard-Smithsonian Center for Astrophysics
Jacob Haqq-Misra – Blue Marble Space Institute of Science
Lisa Kaltenegger – Cornell University
Stephen Kane – UC Riverside
Nikole K. Lewis – Space Telescope Science Institute
Michael R. Line – Arizona State University
Margaret Meixner – Space Telescope Science Institute, Johns Hopkins, NASA/Goddard Space Flight Center
Klaus M. Pontoppidan – Space Telescope Science Institute
Kate Su – University of Arzioan
Gregory S. Tucker – Brown University
Miguel de Val-Borro – NASA Goddard Space Flight Center

Executive summary: Phase curve observations of transiting exoplanets allow for the measurement of their thermal structure with orbital phase and therefore longitude. While these observations have been conducted only for giant exoplanets to date, we anticipate that smaller, more temperate planets will be observed with this technique on future space-based platforms, opening a new window to the chemical, advective and radiative processes that shape the atmospheres of small planets. In this white paper we describe the science that can be unveiled via thermal phase-curve measurements of potentially habitable planets orbiting mid- to late-M dwarfs. These observations can allow for a determination of whether or not these planets may even have atmospheres, and when conducted spectroscopically, can allow for a probe into their vertical thermal structure and three-dimensional climate.

1. Introduction

Identifying habitable, and possibly inhabited, planets around other stars is one of the leading goals of ongoing and upcoming exoplanet surveys. Specifically, terrestrial planets in the "classic" habitable zones (HZs) of mid- to late-M dwarf stars have received significant scrutiny because their transit probability is high, and because the stars themselves are common (recons.org). Current estimates from the *Kepler* primary mission indicate that there are at least ~0.20 terrestrial size (1–1.5 R_E) planets per M-dwarf HZ (Dressing & Charbonneau 2015).

Indeed, M dwarfs have been the subject of many recent planet searches, and several rocky, nearby HZ planets around M-dwarfs have already been discovered (Proxima Centauri b, Anglada-Escude et al., 2016; TRAPPIST-1, Gillon et al. 2016, 2017; LHS-1140b, Dittmann et al. 2017). Follow-up observations, e.g., with Hubble/WFC3 spectroscopy, have begun to characterize these planets. For example, follow-up observations of planets in the TRAPPIST-1 system rule out cloud-free hydrogen-rich atmospheres (de Wit et al. 2016a, 2018). The search for potentially habitable M-dwarf planets will continue into the foreseeable future with ground- and space-based surveys such as MEarth, SPECULOOS, and the upcoming Transiting Exoplanet Survey Satellite (TESS), which are expected to discover dozens of these planets (e.g., Sullivan et al. 2015). With large ground-based facilities (e.g. ELT, GMT, TMT) coming online in the next decade, and space-based flagship missions (e.g., JWST, decadal concepts) concurrently operating along with them, constraints on the three-dimensional (3D) properties of a potentially habitable planet orbiting a M-dwarf is on the horizon.

While transmission and emission spectroscopy can provide key constraints on atmospheric molecular abundances, metallicities, and cloud top pressures (see e.g., Crossfield 2015 for a review), they provide information at only the limb or dayside of the planet, respectively (except perhaps in the case of very hot planets, where nightside emission may contribute to transmission spectra). These observations can therefore be insufficient in describing the fundamentally three-dimensional advective, chemical, and radiative processes in these atmospheres (e.g. Kataria et al 2016, Feng et al. 2016).

Thermal phase-curve observations, which measure the emitted flux of a planet as a function of orbital phase, provides constraints on the planet's temperature structure as a function of longitude. When conducted spectroscopically, these measurements provide constraints in both longitude and altitude, providing a two-dimensional picture of an exoplanetary atmosphere. In this white paper, we provide an overview of how phase-curve observations can provide valuable insights into an exoplanet's three-dimensional atmospheric circulation and climate.

2. Current state-of-the-art: Hot Jupiter characterization

Observations of hot Jupiters (HJs) have shown the wealth of information that can be gleaned from phase-curve observations. The first phase-curve measurements of a hot Jupiter were performed for HD 189733b with Spitzer/IRAC (Knutson et al. 2007). These observations indicated that, as predicted by three-dimensional (3D) general circulation models (GCMs; e.g., Showman & Guillot 2002) the atmospheric dynamics help shape the peak in emitted infrared flux, and the amplitude of the flux variations from dayside to nightside. Since then, phase curves have been observed for a range of HJs over a wide range of physical properties (see Parmentier & Crossfield 2017 for a review). Observations of the ultra-short period (~19 hr) hot Jupiter WASP-43b with the Hubble Space Telescope (HST) Wide Field Camera 3 (WFC3) instrument constitute arguably the highest-fidelity thermal phase-curve measurements published to date. With spectroscopic wavelength coverage from 1.1-1.7 microns, the observations measure the planet's water abundance with orbital phase, and constrain the planet's thermal structure with longitude and altitude (Kreidberg et al. 2014, Stevenson et al. 2014, Kataria et al. 2015). We anticipate that significant inroads will be made with near-term platforms like JWST and future proposed missions such as FINESSE or ARIEL, pushing to ever-smaller planets (see Section 4).

3. The future: phase-curve observations of HZ planets around M-dwarfs

Like hot Jupiters, terrestrial planets in and around the HZs of mid- to late-M-dwarfs are expected to be tidally locked (e.g., Barnes 2017). Therefore, these planets have permanent daysides and nightsides, and rotation periods on the order of days to weeks, much longer than the rotation periods of many solar system planets, including Earth. These properties will play a large role in setting the atmospheric circulation (e.g., Carone et al. 2018). For slower rotators (>20 days), the circulation can exhibit weak radial flow from dayside to nightside and the so-called eyeball climate state, whereby a liquid water ocean only exists near the substellar point (e.g., Pierrehumbert 2010, Angerhausen et al. 2013). Comparatively faster rotators (P~1 day) can exhibit broad upper atmosphere superrotation, or superrotating high-latitude jets with banding (Carone et al. 2018). If the planet is eccentric, pseudo-locking of its orbit and rotation may result in weak seasonal climatic cycles (e.g., Driscoll & Barnes 2015). Each of these circulation regimes will influence the distribution of heat and the formation and transport of aerosols in the planetary atmosphere, all of which will shape thermal phase curves. Here we provide an overview of the atmospheric properties that can be constrained with thermal phase-curve observations for this population of potentially habitable planets.

3.1. Distinguishing between planets with and without atmospheres

Thermal phase curves of tidally-locked, terrestrial planets can be used to simply distinguish between planets with and without atmospheres. More specifically, disk-integrated broadband thermal phase curves can distinguish between a water-rich and a dry/water-poor planet, but also to confirm the presence of substellar clouds (Yang et al. 2013). Tidally-locked, ocean-covered planets, or 'aquaplanets', can exhibit strong and persistent convection at the sub-stellar region, creating an optically thick cloud deck (Yang et al. 2013; Kopparapu et al. 2016, 2017; Wolf 2017). This cloud deck causes a strong increase in the planetary albedo, cooling the planet, and stabilizes its climate against a thermal runaway for large incident stellar fluxes. Thus, an ocean-covered planet can maintain clement global mean surface temperatures (~280 K) around M-dwarf stars at much higher stellar fluxes than Earth. 'Aquaplanet' phase curves will therefore exhibit small amplitudes, with a peak in emitted flux that occurs after superior conjunction (secondary eclipse) due to the water vapor advected eastward of the substellar point that absorbs outgoing thermal radiation. Conversely, a dry planet has larger day-night temperature variations and a lack of clouds, and so exhibits large-amplitude thermal phase variations with a peak at superior conjunction.

3.2. Constraining rotation rate

The rotation rate of the planet can also be constrained by observing thermal phase curves of rocky planets. Assuming ocean-covered worlds, morphological differences between thermal phase curves for planets that are rapid, slow, and intermediate (Rhines) rotators (with rotation periods ranging from ~4 to ~86 days) arise as a result of the interaction of atmospheric dynamics with the formation of upper-atmospheric clouds (Fig 1). Such clouds, in turn, alter both the planetary surface temperature and the allowed outgoing thermal radiation at the top of the atmosphere (Haqq-Misra et al. 2018). The morphology of thermal phase curves can also differentiate synchronous rotators from those in spin-orbit resonances (Wang et al. 2014). Rotation rates can also be constrained for eccentric rocky planets (e.g., Boutle et al. 2017), as has already been demonstrated for eccentric giant planets (de Wit et al. 2016b).

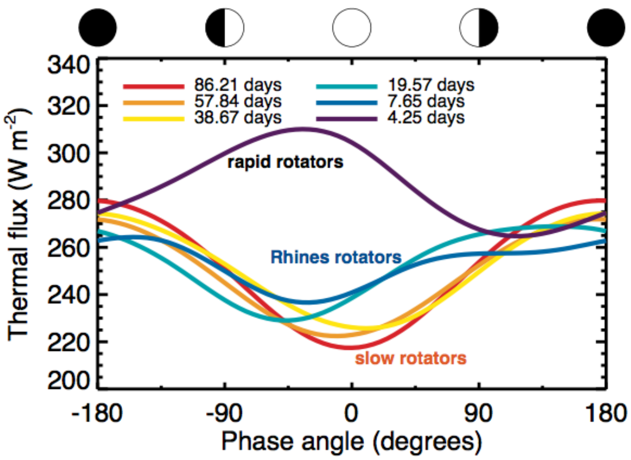

Figure 1: Thermal phase curves of synchronously rotating planets around various late-K and M-dwarf stars. Morphological differences emerge between "rapid", "Rhines" (intermediate) and "slow" rotators. A phase angle of 180 deg corresponds to transit, while a phase angle of 0 deg corresponds to secondary eclipse.

3.3. Distinguishing between climatic types

We may be able to distinguish between different climatic states on rocky planets orbiting M-dwarfs by studying the amplitude and morphology of their thermal emission phase curves. Figure 2 shows thermal emission phase curves from numerous 3D simulated climate states for planets in the TRAPPIST-1 system (Wolf 2017) (solid lines), along with a control simulation of Earth around the Sun (dotted line). An atmosphere in runaway emits strongly (>300 W/m^2) at thermal wavelengths, with maximum emission from a sub-saturated cloud free substellar hot spot. Snowball cases (i.e. fully glaciated worlds) have a low thermal emission (<100 Wm^{-2}) with very little variation across orbital phases. The phase curves of temperate (~285 K) and hot (~330 K) climates are most strongly affected by clouds, with minimum emission eastward of the substellar point, coincident with dominant cloud patterns. However, their thermal emitted phase curves are quite similar, and thus may be difficult to distinguish from each other. Cold climates (i.e. dominated by ice but with some small open-ocean at the substellar point) emit most strongly from their above freezing substeller point. Finally, dry planets, as discussed earlier, have the strongest day-night surface temperature gradients and no clouds by definition, resulting in large amplitude symmetric phase curves.

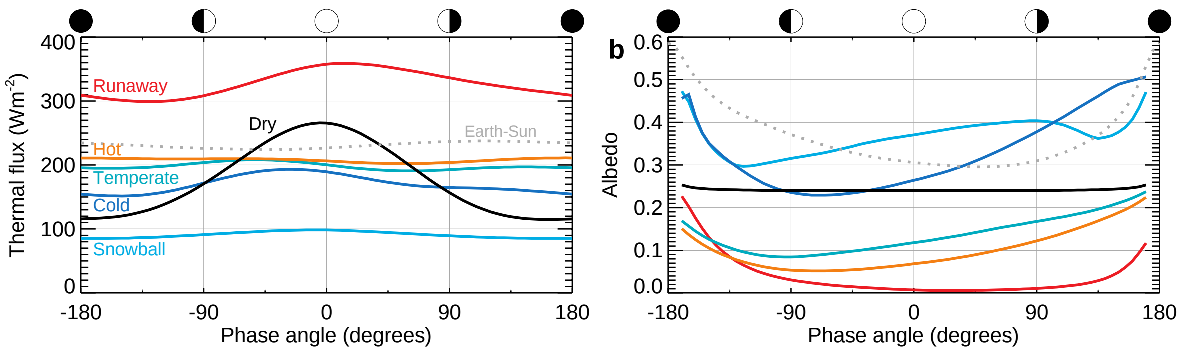

Figure 2: Phase curves of emitted thermal flux and planetary albedo for various possible climate states of the TRAPPIST-1 planets (solid lines). An Earth-Sun phase curve is shown for comparison (dotted line).

3.4. Characterizing the atmospheres of non-transiting planets

Thermal phase-curve observations of non-transiting HZ planets like Proxima Centauri b can also yield information about their physical properties. They can be used to simply detect an atmosphere and distinguish between different atmospheric compositions (i.e., dry planets vs 'aquaplanets'), but also between different rotation rates (i.e., synchronous rotation vs spin-orbit resonances; Turbet et al. 2016). Importantly, thermal phase curves of non-transiting planets can be used to measure the planet's inclination, breaking the mass degeneracy measurement, as has been demonstrated for hot Jupiters (e.g. Crossfield et al. 2010).

4. Prospects with Future Missions

4.1. James Webb Space Telescope (JWST)

JWST is set to revolutionize science of transiting exoplanets, with the capability to characterize ever-smaller planets over a broader wavelength range (e.g. Barstow et al. 2015). A suite of instruments operating from the near- to mid-infrared can be used for exoplanet science, including high SNR phase-curve measurements. While JWST can readily conduct spectroscopic phase-curve observations of numerous warm-to-hot ice and gas giant planets ($R > 4R_E$), it is unlikely that it will have the SNR necessary to measure spectroscopic phase curves for smaller planets (Beichman et al. 2014). Still, using broadband photometry with JWST/MIRI, it may be possible conduct phase-curve observations of terrestrial planets orbiting the nearest, brightest M-dwarfs to determine whether or not these planets have atmospheres, and get a basic temperature constraint. This has been argued in the case of GJ 1132b (Morley et al. 2017), but also for the non-transiting Proxima Centari b (Kreidberg & Loeb 2016).

4.2. Origins Space Telescope (OST)

The Origins Space Telescope is one of the four large concept missions for the 2020 Decadal Survey. OST will operate in the mid- to far-IR, answering an array of questions about the fundamental nature of galaxies, disks, and planets. The telescope would include a mid-IR instrument, the Mid-Infrared Imager, Spectrometer, and Coronagraph (MISC), to conduct exoplanet science with simultaneous wavelength coverage from 5-25 microns. Among its leading scientific goals is the identification of biosignatures in rocky exoplanets in the HZs of M-dwarfs via emission and transmission spectroscopy. However, OST/MISC will also be capable of conducting spectroscopic phase-curve observations of M-dwarf HZ planets, providing a heretofore unseen look at their vertical thermal structure. Importantly, over this wavelength range, we are sensitive to the bulk thermal emission of these temperate planets. Therefore, we can use spectroscopic phase-curves of M-dwarf planets to estimate their total emitted energy budgets. A comparison to the incident radiation then allows us to constrain the bond albedo of a planet. Ultimately, spectroscopic phase-curve observations with OST would enable direct determination of habitability for this unique class of planets.

4.3. Conclusions and Future Outlook

Thermal phase-curve observations offer a wealth of information about the global processes within exoplanetary atmospheres. In the case of small, potentially habitable planets that orbit M-dwarfs, phase curves offer a glimpse into the planet's longitudinal thermal structure, but also its atmospheric composition, rotation, and climactic state. This is true for planets that are both transiting and non-transiting, increasing the yield and opening the door to many nearby systems. Future missions like JWST and especially OST offer the potential to extend our methodologies in understanding the three-dimensional properties of large exoplanets to understanding the exotic climates of potentially habitable worlds. In order to enable future phase-curve observations of potentially habitable M-dwarf exoplanets orbiting M-dwarfs, we recommend the following for the community:

- ***Support for ground- and space-based transit surveys of mid- to late-M dwarfs***. While projections suggest TESS will find ~8 temperate rocky planets (< 300 K, < 1.5 R_E) around M stars < 0.25 M_{Sun}, its wavelength range will limit it from detecting planets orbiting the coolest M dwarfs (such as TRAPPIST-1). Therefore, near-IR surveys such as MEarth and SPECULOOS will be very important for finding planets transiting the cooler M dwarfs that TESS will not probe.
- ***A suite of comprehensive theoretical models investigating the climate of potentially habitable planets under a wide range of conditions.*** Current 3D climate models of exoplanets in the HZ of M-dwarf stars explore only a subset of planetary conditions, and often over a narrow range. For example, varying topography, global surface water distribution and land-ocean fraction can have significant effect on spectral features and phase curves of synchronously rotating planets but have not been explored systematically and coupled with other complex processes (e.g, chemistry). Therefore, a systematic study or set of studies are needed to explore the vast range of climate states that can exist on M-dwarf planets, and how those will affect phase-curve observations of their atmospheres.
- ***Advancement of mid-IR detector technology***. Because thermal phase-curve measurements like these would be conducted at mid-IR wavelengths (where the peak emission of temperate rocky planets lie), advancement in mid-IR detectors is necessary to achieve the necessary precision for spectroscopy.

References: Dressing & Charbonneau 2015; Anglada-Escude et al. 2016; Gillon et al. 2016, 2017; Dittmann et al. 2017; de Wit et al. 2016, 2018; Sullivan et al. 2015; Crossfield 2015; Kataria et al. 2016; Feng et al. 2016; Knutson et al. 2007; Showman & Guillot 2002; Parmentier & Crossfield 2017; Kreidberg et al. 2014; Stevenson et al. 2014; Kataria et al. 2015; Barnes 2017; Carone et al. 2018; Pierrehumbert 2010; Angerhausen et al. 2013; Driscoll & Barnes 2014; Yang et al. 2013; Kopparapu et a.. 2016, 2017; Wolf 2017; Haqq-Misra et al. 2018; Wang et al. 2014; Boutle et al. 2017; de Wit et al. 2016b; Wolf 2017; Turbet et al. 2016; Crossfield et al. 2010; Barstow et al. 2015; Beichuan et al. 2014; Morley et al. 2017; Kreidberg & Loeb 2016

Part of the research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.