Astro2020 Science White Paper

The Importance of Thermal Emission Spectroscopy for Understanding Terrestrial Exoplanets

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

Principal Author:
Name: Michael R Line
Institution: Arizona State University
Email: mrline@asu.edu
Phone: 920-360-0536

Co-authors:
Sascha P. Quanz (ETH Zurich), Edward W. Schwieterman (UCR), Jonathan J Fortney (UCSC), Kevin B. Stevenson (STScI), Tom Greene (NASA Ames Research Center), Robert Zellem (JPL), Caroline Morley (UT-Austin), Tiffany Kataria (JPL), Luke Tremblay(ASU), Bertrand Mennesson (JPL), Aishwarya Iyer (ASU), Dimitri Mawet (Caltech), Nicolas Iro (University of Vienna), Lisa Kaltenegger (Cornell), Denis Defrere (University of Liege)

Co-signers: Edwin S. Kite (University of Chicago), Douglas A. Caldwell (SETI Institute), Evgenya Shkolnik (Arizona State University), Diana Dragomir (MIT/UNM), Franck Marchis (SETI Institute), Henry Ngo (NRC Canada), Jasmina Blecic (NYUAD), Tim Lichtenberg (University of Oxford), Daniel Angerhausen (Bern University), Arif Solmaz (Çağ University), Eric T. Wolf (CU Boulder), John Monnier (UMichigan), Stephen R. Kane (University of California, Riverside), William Danchi (NASA/GSFC), Keivan Stassun (Vanderbilt University), Diana Valencia (University of Toronto), Johannes Staguhn (JHU & NASA-GSFC)

Introduction

We can remotely sense an atmosphere by observing its reflected, transmitted, or emitted light in varying geometries. This light will contain information on the planetary conditions including atmospheric composition, surface temperature/pressure, cloud/aerosol properties, and weather. Each of these approaches/techniques carry both complementary and redundant information as well as their own unique challenges in interpretation. The challenge is in deciding the optimal observational "regime(s)" (or combinations thereof) to characterize terrestrial planet atmospheres. ***The goal of this white paper is to reiterate the importance of the thermal (~3 - 50 um) emission spectroscopy regime for characterizing planets beyond our solar system.***

Why is Planetary Thermal Emission Important?

For most planets, the energy budget of a planetary atmosphere is dominated by the absorption and re-radiation of stellar energy (1). ***The temperature structure of the atmosphere (its temperature as a function of height or pressure) is a diagnostic and a driver of planetary chemistry and climate.*** An emission spectrum simultaneously encodes information about this temperature structure and molecular abundances as well as the re-radiated luminosity of the planet. If we are to understand the climates of terrestrial planet atmospheres, we need emission spectra. In particular, the mid-IR (MIR) ***is a critical wavelength regime as it presents multiple absorption features of multiple major molecules required to explore planetary conditions. For terrestrial planets, the MIR can access signs of life: the combination of ozone with methane (and/or N_2O), which is a much more challenging observation in the visible.*** The importance of the MIR is well known to the Earth and planetary science communities. ***Most Earth-bound climate and weather satellites contain thermal emission sensitive instruments.*** For instance, global weather forecasting relies upon space-based nadir sounding data obtained between ~4 and 13 microns (GOES-R, 2) to retrieve the humidity, surface and tropospheric temperatures, and cloud-top temperatures. Furthermore, decades of solar-system missions have relied upon thermal emission measurements to accomplish their key science goals.

Lessons Learned from ~15 Years of Extrasolar Giant Planet Science

The community has made outstanding progress in understanding the nature of hot extrasolar Jovian-like worlds ($T > 600K$, $R > 4R_E$). From this experience, we've learned that thermal ***emission measurements are key to constraining atmospheric composition, thermal structure, climate, and circulation*** (e.g., 3-10). Emission spectroscopy has been the *only* approach for understanding the atmospheric properties of young directly-imaged planets thus far (e.g., 11-13)

Composition: A key driver of exoplanet science of the past decade has been atmospheric atomic/molecular abundance determinations, to look for enhancements compared to parent star composition, and to understand ratios between these species. Identifying differences in atmospheric elemental abundances when compared to the parent star composition aid in testing planetary formation models (e.g., 14-16). ***Infrared (IR) wavelengths provide multiple strong molecular bands*** for the most important C, N, and O-bearing molecules. ***The strength of multiple bands is critical to overcoming degeneracies*** inherent in fitting models to spectra (e.g., 17) leading to more stringent abundance constraints.

Thermal IR ***emission observations are also much less influenced by the presence of clouds; clouds are currently the largest uncertainty in atmospheric modeling*** (18,19). Transmission spectra are easily influenced by particulates due to the slant path geometry (20). Reflected light spectra largely rely on a bright scattering layer to increase signal and are also in a regime sparse in strong molecular absorbers. Interpretations of spectra in these two regimes are therefore highly dependent upon the cloud modeling assumptions. However, long-wave IR spectra, due to the much stronger molecular opacity relative to cloud opacity (per "unit-cloud") and simpler geometry, are much less sensitive (though not entirely insensitive) to the cloud modeling assumptions. ***Mitigating the role of uncertain cloud properties is imperative to our understanding of atmospheric composition.***

Vertical Structure, Climate, & Circulation: ***Thermal emission observations have proven to be the only reliable way of determining the vertical thermal structure of extra-solar atmospheres.*** Highly irradiated hot Jupiter's were hypothesized to possess stratospheric inversions (similar to Earth's ozone induced inversion) due to the presence of strongly UV/optical absorbing metal oxides (21). IR Emission observations were critical to determining the presence of these inversions via the detection emission features over the HST and Spitzer wavelength ranges (e.g., 9) as well the molecular absorbers causing them (22-24). Assessing the plausibility of the existence and abundances of these species, through chemical arguments, is dependent upon our knowledge of the thermal structure. ***Furthermore, the vertical thermal structure is the key property governing the presence of obscuring equilibrium condensate clouds and the dominant molecular species in Jovian worlds***. Broad wavelength coverage ***emission spectroscopy of both the day and night "sides" of an irradiated transiting planet allow for a full accounting of the global energy balance*** (e.g., 25,26,4) allowing for the derivation of the planetary bond albedo. More ambitious phase curve observations of tidally locked planets (hence longitude) directly probe the day-to-night heat transport (e.g., 27, 28), global cloud coverage (24,29), and horizontal variations in gas-phase chemistry (30).

The Need for Thermal Emission in Characterizing Temperate Terrestrials

Temperate terrestrial worlds will be much cooler (~300K) than many planets characterized thus far. Nearly 90% of their thermal radiation will emit between 5 and 30 um. ***In order to address similar fundamental questions about atmospheric composition, climate, and circulation, MIR wavelengths will necessarily be required.***

Is this Planet Terrestrial? ***Establishing if a planet is rocky is one of the first steps in determining its habitability prospects.*** Current exoplanet demographics suggest that rocky or "terrestrial" planets typically have radii less than ~1.5 that of Earth (31,32). Transiting planet characterization will always have the advantage of well-known masses/radii (within precision limits). However, most terrestrial worlds we are likely to characterize in the future will *not* be transiting due to statistics and the intrinsic stellar photon noise limit for transiting planets. Reflected light observations, while incredibly diagnostic of planetary conditions (e.g., 33,34), suffer from the inherent albedo-vs.-radius degeneracy. ***Without knowing a-priori the reflectivity of the planet, the radius could be unknown up to a factor of~7*** (35) ***which could mean the difference between***

a terrestrial planet, a Super-Earth, or a Neptune-like world (36). ***Thermal emission spectroscopy, however, (through imaging) does not suffer from the albedo-radius degeneracy***. If the distance is known, like with brown dwarfs (e.g., 37,38), the radius can be obtained photometrically as the planetary temperature information is encoded independently within the spectral shape.

Composition and Bio-Indicators: The thermal IR is a rich spectral region for detecting biosignature gases including the chemical disequilibrium between them (39, 40) and this has generally been true throughout geologic time on our own planet (41). ***Studies of the geochemical evolution of Earth's atmosphere suggest that false negatives for remote life detection may be common in reflected light*** because Vis/Near-IR (NIR) spectral features for O_2 did not co-occur with substantial CH_4 (> 10 ppm) and correspondingly detectable NIR features at low spectral resolving powers (42). However, CO_2-CH_4 disequilibrium is suggested as a biosignature for reducing atmospheres like the Archean Earth (4.0-2.5 Ga; 43) with CO_2 and CH_4 producing the strongest spectral features in the MIR (15 um and 7.7 um, respectively). After the Great Oxidation Event (44), the most potentially detectable bio-indicator for Earth's atmosphere was the disequilibrium between O_2 and CH_4 (e.g., 45), which is revealed in the MIR via the simultaneous presence of O_2's photochemical product, O_3 (9.65 um) and the strong CH_4 band at 7.7 um. The MIR also includes strong signatures from H_2O (5-7 um; >17 um), a key requirement for planetary habitability, and N_2O (7.6-8.8 um), another biosignature gas produced by microbes via incomplete denitrification. The presence of CO_2 and H_2O also informs planetary climate. The vertical distribution of H_2O in the atmosphere is important for determining the presence of oceans and its impact on photochemistry may suggest that biosignature trace gases possess a strong and active source (39). In general, detecting biosignature pairs and establishing planetary context is important in part to rule out abiotic mechanisms for putative biosignature production (35), which is strongly supported by MIR observations.

Thermal Structure, Climate, and Circulation: Thermal emission observations of terrestrial planets are the only way to determine the surface (or deepest layer) temperature, presence/absence of a stratospheric inversion, and tropospheric lapse rates (e.g., dry or moist adiabat). These quantities in turn provide context for the inferred composition (e.g., is there a water cold trap at the tropopause?, is there an ozone induced inversion?) and the basic planetary climate. ***Thermal emission phase curve observations of a tidally locked terrestrial planet (transiting or non-transiting) can be used to determine if that planet has an atmosphere*** (46). An airless body would show strong "day-to-night" temperature contrast (e.g., like Mercury). Furthermore, in non-tidally locked planets (e.g., Earth), variability with time could be indicative of weather, as observed in brown dwarfs (47), or of variable surface features (land/ocean/ice) due to changing emissivity's (48)

Future Thermal IR Spectroscopy Platforms for Terrestrial Planets

JWST: JWST will be the first observatory to obtain high-precision (< 50 ppm), moderate spectral resolving power (R > 100) emission spectra for warm-to-hot planets over wavelengths of ~1 - 11 um containing key information for the determination of vertical temperature profiles, molecular abundances, and planetary climate through phase resolved observations (e.g., 49,50). However, the ***JWST instruments are not optimized for precision terrestrial planet atmosphere observations***; covering this large wavelength range will require observing 3 or 4 secondary eclipses (or as many observations per planetary phase) and the instruments may have systematic noise floors. Ultimately, JWST's capabilities will not be truly known until it acquires on-sky data. The first tests of its precision will likely come from the Transiting Exoplanet Community ERS program (51), which will perform a full-orbit phase curve observation using MIRI and observations of a bright source using NIRISS/SOSS, both probing the thermal emission spectrum of the planets.

OST: The Origins Space Telescope large mission concept will improve on JWST's performance by observing the 3-20 um spectral range simultaneously and will minimize systematic noise by incorporating a densified pupil spectrograph design (52,53). Adding to this its larger field of regard (relative to JWST), ***Origins is expected to achieve the necessary precision to constrain a temperate terrestrial planet's thermal structure and assess the likelihood of liquid water on its surface (see white paper by Kataria et al.)***.

Ground-Based: Detecting thermal emission from terrestrial exoplanets is extremely challenging from the ground due to the high thermal background from Earth's atmosphere and the telescope. ESO is currently preparing the NEAR experiment in collaboration with the Breakthrough Foundation, where the goal is to upgrade the VISIR mid-IR imager at the VLT with an adaptive optics system and an optimized filter and vortex coronagraph centered at ~11.2 um to search for a (super)Earth companion in the habitable zone around Alpha-Centauri in a 100-h observing campaign in summer 2019 (54). Going from 8-10 m class telescopes to the 30-40 m ELTs will significantly reduce the required telescope time for such an experiment.[1] Searching for the thermal emission of terrestrial planets around the nearest stars in the L, M or N band is one of the prime science cases for the MIR ELT Imager and Spectrograph (METIS) for the European ELT (55) and also PSI and MICHI at the TMT (56). ***However, even in the era of the ELTs only a handful of stars in the immediate vicinity of the Sun can be probed for true Earth analogs*** as for more distant objects the required time-on-target becomes prohibitively long.

Nulling Interferometry: ***In the long run, in order to investigate the atmospheric diversity of dozens of terrestrial exoplanets via their thermal emission, one has to go to space.*** While the thermal background noise is less of a challenge, the required spatial resolution is, and only nulling interferometry is able to provide sufficient spatial resolution, contrast and sensitivity to allow for the detection of small planets orbiting stars within 20-25 pc (e.g., 57-59). This approach was already actively pursued more than a decade ago with NASA's TPF-I concept (59) and the ESO Darwin mission (60), which, in the end, both were not implemented. Since then long-term radial velocity and transit surveys have significantly advanced our understanding of the exoplanet population allowing a much more robust estimate of the expected yield of a space-based mid-IR nulling interferometer (58), which may even exceed that of large, space-based Vis/NIR telescopes searching for planets in reflected light. Furthermore, key technologies, e.g., formation flying and

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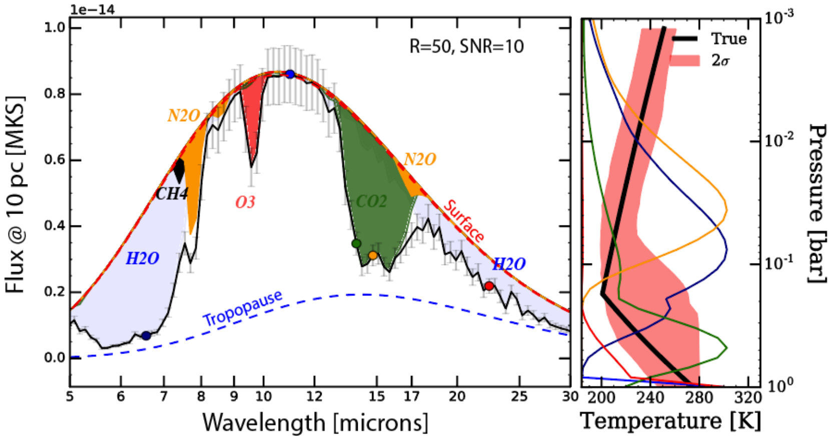
[1] In the background limit the time to complete an observation with a fixed SNR scales with $1/D^4$.

starlight suppression, were developed further and have reached a promising readiness level (40), as well as record-braking dynamic ranges with ground-based nulling interferometers such as the Keck Interferometer Nuller and the Large Binocular Telescope Interferometer (61, 62). One of the next steps is to reassess key science requirements in terms of wavelength coverage, spectral resolution and required SNR (cf. 63). Preliminary simulations suggest that the 3-30 um range with an R~50 and SNR of 10 is sufficient to search for and identity the suspected main molecular constituents and robustly derive abundance ratios (Figure 1, and 64). This is broadly consistent with the requirements for TPF-I/Darwin (39).



	R=50, SNR=10
Surface Temperature [K]	+/- 3
Log Surface Pressure [bar]	+/- 0.3
Troposphere Lapse Rate [dlnT/dlnP]	+/-0.02
H2O	150x
CH4	275x
CO2	148x
O3	123x
N2O	145x
CO	U.L. < 10 ppm
Radius	+/- 1%

Figure 1: Simulation of a cloud-free Earth at 10 pc in the Mid-IR (left, black line) as observed with a space-based interferometer with a R=50, SNR=10 (light grey error bars). The key molecular absorbers are highlighted along with the surface and tropopause blackbodies. The colored dots indicate the wavelengths for which the thermal emission contribution functions are shown in the middle panel. The middle panel shows the temperature structure (black) and the thermal emission contribution functions (colored curves—where the emission originates at that wavelength). The pink error envelope represents the potential temperature structure constraints under the R=50, SNR=10 setup. The table on the right illustrates potential constraints on key properties. Abundance constraints are given as a "to within factor".

Final Thoughts

We have illustrated above that the MIR thermal emission is rich in the information required to characterize temperate terrestrial planets and to assess their potential habitability. Such emission observations are able to provide information regarding the thermal structure (including surface temperature and pressure), planetary radius, presence/absence of an atmosphere (through phase curve observations), and meaningful molecular/bio-signature gas abundance constraints. ***We strongly encourage the community to support the need for space-based mid-IR platforms for addressing the Earth 2.0 challenge.*** Ultimately, a complete understanding of temperate terrestrial worlds will have to rely upon a synergistic approach utilizing a combination of emitted, transmitted, and reflected light from both space and ground-based platforms.

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