A New Method for Studying Exoplanet Atmospheres Using Planetary Infrared Excess

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Abstract

To date, the ability for observers to reveal the composition or thermal structure of an exoplanet’s atmosphere has rested on two techniques: high-contrast direct imaging and time-series observations of transiting exoplanets. The former is currently limited to characterizing young, massive objects while the latter requires near 90° orbital inclinations, thus limiting atmospheric studies to a small fraction of the total exoplanet population. Here we present an observational and analysis technique for studying the atmospheres of non-transiting exoplanets that relies on acquiring simultaneous, broad-wavelength spectra and resolving planetary infrared emission from the stellar spectrum. This method could provide an efficient means to study exoplanet atmospheric dynamics using sparsely sampled phase curve observations or a mechanism to search for signs of life on non-transiting exoplanets orbiting the nearest M-dwarf stars (such as Proxima Centauri). If shown to be effective with James Webb Space Telescope observations, the method of measuring planetary infrared excess would open up the large population of nearby, non-transiting exoplanets for atmospheric characterization.

Unified Astronomy Thesaurus concepts: Exoplanet atmospheres (487); Exoplanet detection methods (489)

1. Introduction

Using available instruments, it is currently impossible to determine an unresolved planet’s absolute flux without observing it pass behind its host star. This is because the secondary eclipse provides a reference point in time for which there is no planetary emission. Non-transiting exoplanets do not have access to this reference point and, thus, currently only yield a relative flux when observed. Early works with Spitzer Space Telescope (Werner et al. 2004) observations of the non-transiting exoplanet υ Andromæææ b demonstrate the challenges of producing reliable results with sparsely sampled photometric data (Harrington et al. 2006; Crossfield et al. 2010). With relatively broad wavelength coverage, James Webb Space Telescope (JWST’s) spectroscopic instruments will be capable of inferring the absolute flux of hot, and even warm, exoplanets by way of a reference point in wavelength.

2. Conceptualization

Figure 1 provides a qualitative visualization of the planetary infrared excess (PIE) technique. It depicts the spectral intensity from a 4400 K blackbody with and without a 1000 K blackbody that has been enhanced by a factor of 1000. Although this scenario applies to the exoplanet system WASP-43 with and without planetary nightside emission, it is also representative of many other hot Jupiters, which have been shown to have uniform nightside temperatures of ~1000 K (Beatty et al. 2019; Keating et al. 2019). These warm planet nightsides emit no measurable flux at <1.3 mμ, thus providing a suitable reference wavelength range to constrain the stellar spectral energy distribution (SED). When measured simultaneously at longer wavelengths (e.g., 1.3–5 mμ), one can compare the extrapolated stellar models to the observational data and infer that the measured infrared excess originates from the planet. This is akin to performing a two-component SED fit to identify unresolved binary stars (Burgasser et al. 2010; El-Badry et al. 2017), except here, the extreme difference in signal size between the two bodies requires the stability and precision of a space-based observatory. In general, the large temperature difference can help to distinguish the planet’s peak SED in wavelength space from that of its host star. The PIE method is also conceptually similar to attributing infrared excess to circumstellar disks when the stellar SED has a greater measured infrared flux than expected from that of a blackbody.

3. Demonstration

As an initial demonstration of the PIE technique, we simulate WASP-43 (R_S = 0.667 R_J) as a T_S = 4400 K blackbody and WASP-43b (R_P = 1.036 R_J) over a range of nightside blackbody temperatures (T_P = 500–2500 K). We consider two wavelength ranges representing JWST’s NIRISS/ SOSS instrument mode alone (0.8–2.8 μm; Doyon et al. 2012) and paired with JWST’s NIRSpec/G395H mode (0.8–5.0 μm total; Ferruit et al. 2012). We use PandExo to generate realistic uncertainties (Batalha et al. 2017), assuming one hour of observation per mode. When retrieving the best-fit parameters (R_S, T_S, R_P, T_P), we adopt a fixed planet radius to simulate a transiting planet of known size and a uniform prior to simulate a non-transiting planet of unknown size. We assume zero albedo for all cases, though a planet’s nightside flux has no reflected light component.

Figure 2 depicts the results of our experiment. For each of our four simulations, we see a “sweet spot” in planet temperature that yields the smallest uncertainties (as precise as ±7 K). Increasing the wavelength coverage to 5.0 μm extends the sweet spot to cooler planets. Evidently, resolving the sharp increase in flux on the short-wavelength (Wien) side of the planet’s blackbody emission is crucial to constraining its temperature, which is not possible with broadband photometric observations.

When fitting for the planet radius, which is necessary for non-transiting exoplanets, there can be a strong degeneracy between the retrieved radius and temperature (see Figure A2 in the Appendix). This degeneracy leads to the larger temperature...
uncertainties seen in the left panel of Figure 2; however, utilizing broader wavelength coverage reduces its impact. The right panel of Figure 2 illustrates the planet radius constraints from our two simulations with uniform priors. Again, fitting for the planet radius benefits from utilizing broader wavelength coverage to resolve parameter degeneracies. Stitching together spectra from multiple instrument modes (in this case NIRISS/ SOSS and NIRSpect/G395H) will be explored early in Cycle 1 with JWST’s Transiting Exoplanet Early Release Science Program (Bean et al. 2018).

4. Applications

4.1. Sparsely Sampled Phase Curves

In addition to determining a planet’s radius and brightness temperature, constraining the wavelength dependence of the infrared excess would provide information about its atmospheric composition. Furthermore, this concept could be used to constrain the longitudinal variations in composition of an exoplanet atmosphere (Stevenson et al. 2017) using sparsely sampled phase curve observations (Krick et al. 2016). Currently, most exoplanet phase curves utilize time-consuming observations that start just prior to secondary eclipse and end shortly after the subsequent eclipse (e.g., Knutson et al. 2012; Maxted et al. 2013; Mansfield et al. 2020). Having two reference points in time allows the observer to constrain the planet’s nightside emission, which typically occurs near primary transit. With the PIE technique, every spectroscopic frame provides a reference point in wavelength space that could, in principle, be calibrated against instrument or stellar variability (Wakeford et al. 2019; Arcangeli et al. 2020). Sparsely sampled phase curves would be an ideal means to study atmospheric dynamics over a wide range of orbital periods and planet properties.

Even for the quietest and slowest rotators, stellar variability can cause changes to the measured spectrum that are orders of magnitude larger than a planet’s emission signal. Stellar variability could be removed by first reconstructing the measured stellar flux using multiple temperature-dependent components representing spots and/or plages on a constant photosphere. Wakeford et al. (2019) demonstrate this step by successfully reconstructing TRAPPIST-1’s spectrum using three weighted stellar model components. Next, to build up a more complete stellar model that spans the duration of an observation, the reconstructed stellar spectrum would need time-dependent components. These can vary smoothly with stellar rotation or be stochastic events like flares. Differentiating exceptionally cool plages from planetary emission should be feasible so long as the stellar rotational and planet’s orbital periods are not related by a ratio of small integers. Accurate stellar flare models will be critical toward fitting time-series data of active M-dwarf stars. Finally, by evaluating the reconstructed stellar model on a frame-by-frame basis, one can build a reliable, long-time-baseline reference point in wavelength. Dividing the time-series data by this model will yield the planet’s phase-dependent emission spectrum.

4.2. Nightside Temperature with Transit Observations

Initial tests of the PIE technique with JWST data should focus on transiting exoplanets with measured secondary eclipses. For single-planet systems (like most hot Jupiter systems) data acquired during secondary eclipse will yield a pristine stellar spectrum. Assuming any instrument or stellar variability is mostly achromatic, the measured stellar spectrum can be scaled to fit the reference wavelength range (see Figure 1) for individual frames acquired at any other orbital phase (such as primary transit or quadrature). Recall that any discrepancy between the scaled stellar spectrum and the observed flux at longer wavelengths can be attributed to the planet. Thus, baseline time-series data acquired outside of primary transit could be used to constrain a planet’s nightside emission. Having both a primary transit and secondary eclipse observation over the same wavelength range should be sufficient to measure a planet’s day–night heat redistribution, thus potentially removing the need for full-orbit phase curve observations. If shown to be effective, the PIE technique could open the door for JWST to measure the atmospheric heat redistribution of any hot Jupiter exoplanet with both transit and eclipse observations.

Recent work using the Hubble Space Telescope (HST) to measure the relative thermal emission of WASP-12b at quadrature (Arcangeli et al. 2020) demonstrates the real-world feasibility of the PIE technique when faced with relatively large instrument or astrophysical systematics. Their technique relies on applying common-mode corrections to remove instrument systematics then comparing the extracted spectra at each HST orbit to the pristine stellar spectrum measured during eclipse. They attribute any differences in flux to planetary emission. WASP-12b’s measured brightness temperature at quadrature (2124 ± 314 K) is consistent with Spitzer Space Telescope constraints from full-orbit phase curves at 3.6 and 4.5 μm. Arcangeli et al. (2020) were unable to extract the planet’s nightside temperature due to a shift in the position of the spectrum on the detector relative to the eclipse and quadrature observations.

4.3. Direct Imaging

In addition to simulating Jupiter-size exoplanets, we investigate how the PIE technique could be used to constrain the radii of long-period planets discovered by future high-contrast direct imaging missions such as the Roman Space Telescope, HabEx, or LUVOIR (Akeson et al. 2019; The LUVOIR Team 2019;
over a range of simulated planet nightside temperatures. Uncertainties are shown for both transiting representing planets with known and unknown radii, respectively. Left: for our example exoplanetary system with blackbody emission well constrained with NIRISS uncertainty appreciably for cooler planets uncertainties by also (smaller uncertainties). Right: for the non-transiting hot Jupiters in our simulations, the planet radius is well constrained with NRISS/SOSS alone (ΔR_P < 0.1 R_J for T > 1,400 K and 0.8–2.8 μm). Adding wavelength coverage at longer wavelengths reduces the radius uncertainty appreciably for cooler planets (ΔR_P < 0.1 R_J for T > 850 K and 0.8–5.0 μm).

4.4. Habitability

Finally, we consider how the PIE technique could be used to help future missions search for signs of life. The Origins Space Telescope (hereafter Origins) mission concept was designed to search for biosignatures on planets transiting the nearest M-dwarf stars (Meixner et al. 2019). Relative to Sun-like stars, M-dwarf planet-to-star flux ratios are much more favorable and, thus, the PIE technique should yield more precise planet temperatures and radii. The first two steps in Origins’ exoplanet observing strategy are to confirm the presence of an atmosphere and constrain the planet’s surface temperature to be within the habitable zone. For non-transiting exoplanets, the first step could be readily accomplished by comparing the measured dayside and nightside emission. Assuming non-zero orbital inclinations, planets with tenuous atmospheres (like Mars) will exhibit strong day–night contrasts, whereas those with thick atmospheres (like Venus) will display no measurable variation (Seager & Deming 2009; Selsis et al. 2011; Kreidberg et al. 2019). Importantly, it may be possible to constrain these planets’ orbital inclinations with multi-epoch, high-resolution, cross-correlation techniques (Buzard et al. 2020).

We demonstrate how the PIE technique could achieve Origins’ second step in their observing strategy by simulating Proxima Centauri b, the nearest potentially habitable exoplanet (Anglada-Escudé et al. 2016). Figure 4 illustrates the retrieved planet temperature (with 1σ uncertainties) as a function of observing time for three telescopes: JWST, Origins, and Mid-InfraRed Exoplanet CLimate Explorer (MIRECLE; Staguhn et al. 2019). Regardless of its estimated noise floor, JWST’s Mid-Infrared Instrument/Low Resolution Spectrometer (MIRI/LRS) mode (5–13 μm; Kendrew et al. 2018) is unlikely to precisely constrain Proxima Centauri b’s temperature or radius due to having insufficient coverage at longer wavelengths. With its broad, simultaneous wavelength coverage (3–20 μm), the 6 m Origins is predicted to constrain Proxima Centauri b’s brightness temperature to be within the inner and outer edges of the optimistic habitable zone (Kopparapu et al. 2017) with confidences of 3.5 and 5.7σ, respectively, by observing the system for 10 hours. A 2 m MIRECLE mission concept (also 3–20 μm) would require ∼100 hours to achieve the same detection significance.
of the nearest habitable zone sustain liquid water on their surfaces. We apply the PIE technique to a simulation of the nearest habitable zone (HZ) exoplanet, Proxima Centauri b, using four telescope/instrument configurations: JWST/MIRI (5–13 μm, 0 and 30 ppm noise floor), MIRECLE (3–20 μm, 2 m aperture), and Origins (3–20 μm, 6 m aperture). JWST is unlikely to precisely constrain the planet’s temperature without significant telescope time (>1000 hours) and a much lower noise floor than current expectations (<30 ppm). With 10 hours of integration time, Origins can constrain the simulated planet’s temperature (green shaded region) to within ±15 K and its radius to within ±0.1 Earth radius (not shown). Being a smaller version of Origins, MIRECLE requires ~100 hours to achieve the same precision (purple shaded region). Lines depict the median of the retrieved temperatures and shaded regions depict 1σ uncertainties.

The third (and final) step in Origins’ observing strategy is to search for biosignatures. There are numerous molecular features in the mid-infrared that would be good indicators of life (e.g., O3+CH4 or O3+N2O); however, more work is needed to determine whether or not the PIE technique could be used to identify these pairs of molecular features in non-transiting exoplanet atmospheres (see the Appendix). If shown to be capable, a mid-infrared mission (such as Origins) could characterize the atmospheres of ~240 temperate, terrestrial worlds within 15 pc (Barclay et al. 2018). Many of these non-transiting exoplanets will be discovered this decade by ground-based radial velocity surveys focused on identifying planets orbiting the nearest M-dwarf stars (Crepp et al. 2016; Claudi et al. 2018; Seifahrt et al. 2018).

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Appendix

A.1. Methods

We load exoplanet system parameters from exo.MAST1 and compute missing entries using publicly available code2 written for the Exoplanet Atmosphere Observability Table (EAOT; Mullally et al. 2019). We use Pandexo to generate realistic uncertainties for JWST’s NIRISS/SOSS and NIRSpec/G395H instrument modes. Our final results use spectra that have been binned to a resolving power of 100. Tests show that using spectra at the native resolution of the instruments does not impact our results. To estimate realistic uncertainties with Origins and MIRECLE, we use custom code originally written by T. Greene (personal communication). This is the same code adopted for the Origins Mission Concept Study Report (Meixner et al. 2019). Since our goal is to assess the magnitude of our parameter uncertainties, we do not add noise to the simulated data. Doing so would potentially drive the median away from the true value and prevent us from identifying biases in the retrieved results.

For all of our retrievals, we use a nested-sampling algorithm (Skilling 2004, 2006), as implemented by DYNESTY (Speagle 2020). For the transiting exoplanet simulations, the log-likelihood function uses the reported transit depth to constrain the planet-to-star area ratio. This has the benefit of providing a tight constraint on the planet radius since the stellar size and temperature are almost always well constrained in our simulations. We initialize each run using 500 live points spread uniformly across our defined prior region with multiple bounding ellipsoids (Feroz et al. 2009). Valid prior regions vary for different simulated exoplanet systems, but are always consistent within a related set of simulations. Figures A1 and A2 provide two example correlation pairs plots with 1D marginalized posteriors for Origins and JWST, respectively. These figures demonstrate how parameter degeneracies vary with wavelength coverage.

A.2. Future Work

It is important to understand the limits of our blackbody simulations and how to improve upon them. The simulations presented here have yielded best-case uncertainties due to the simplified (blackbody) representation of our objects and limited number of free parameters (temperature and radius). Future work will need to incorporate more complex models to address a series of potential obstacles. These include:

1. constraining the planet’s thermal structure and atmospheric composition using realistic stellar and planetary models;
2. quantifying the impact of a non-zero, wavelength-dependent planet albedo at various orbital phases;
3. resolving the potential degeneracy between planet size and orbital inclination;
4. correcting for achromatic stellar variability;
5. characterizing individual planets in multi-planet systems.

Upon completion of a more in-depth study, we will be able to better assess the validity of the PIE technique to accurately determine a planet’s absolute flux under more realistic conditions. From there, we can establish the wavelength range, resolving power, and precision necessary to successfully implement the PIE technique with data from future observatories. These values will likely depend on the stellar type, planet size and temperature, and the scientific goal that one hopes to achieve. For example, we expect that assessing the habitability of a terrestrial M-dwarf planet will have different requirements than a hot Jupiter orbiting a G dwarf.

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1. https://exo.mast.stsci.edu/
2. https://github.com/kevin218/exoMAST_Obs
Ultimately, it is important to determine which goals can be met using one or more of JWST’s instrument modes. This theoretical work can then be followed up with analyses using actual JWST data. If shown to work for hot Jupiters and warm Neptunes with JWST, these benchmarks should enable us to extrapolate the outcome when observing potentially habitable worlds.

Looking forward, the combined theoretical and observational results can help guide future instrument and mission concept development (such as a 6 m Origins or a smaller MIDEX or Probe-class telescope) to address the findings laid out in the National Academies’ 2018 Exoplanet Science Strategy and 2019 Astrobiology Strategy (National Academies of Sciences & Medicine 2018, 2019).

Figure A1. Example correlation pairs plot with 1D marginalized posteriors for a simulation of the Proxima Centauri system using 10 hours of integration time and a 6 m Origins-like telescope. In order, the free parameters include planet temperature (K), stellar temperature (K), planet radius ($R_p$), and stellar radius ($R_\star$). Solid red lines indicate the truth. Dashed blue lines represent the 16%, 50%, and 84% credibility regions (i.e., median with 1σ uncertainties). With precise, broad wavelength coverage, we are able to minimize the planet’s radius–temperature degeneracy. The stellar parameters in these simulations are more tightly constrained than would be the case if we were to use more realistic model stellar spectra.
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References

Akeson, R., Armus, L., Bachelet, E., et al. 2019, arXiv:1902.05569
Anglada-Escudé, G., Amado, P. J., Barnes, J., et al. 2016, Natur, 536, 437
Arcangeli, J., Desert, J.-M., Parmentier, V., Tsai, S.-M., & Stevenson, K. B. 2020, A&A, submitted
Barclay, T., Pepper, J., & Quintana, E. V. 2018, ApJS, 239, 2
Batalha, N. E., Mandell, A., Pontoppidan, K., et al. 2017, PASP, 129, 064501
Bean, J. L., Stevenson, K. B., Batalha, N. M., et al. 2018, PASP, 130, 114402
Beatty, T. G., Marley, M. S., Gaudi, B. S., et al. 2019, AJ, 158, 166
Burgasser, A. J., Cruz, K. L., Cushing, M., et al. 2010, ApJ, 710, 1142
Buzard, C., Finney, L., Piskorz, D., et al. 2020, AJ, 160, 1
Claudi, R., Benatti, S., Carleo, I., et al. 2018, Proc. SPIE, 10702, 107020Z
Crepp, J. R., Crass, J., King, D., et al. 2016, Proc. SPIE, 9908, 990819
Crossfield, I. J. M., Hansen, B. M. S., Harrington, J., et al. 2010, ApJ, 723, 1436
Doyon, R., Hutchings, J. B., Beauvieu, M., et al. 2012, Proc. SPIE, 8442, 84422R
El-Badry, K., Rix, H.-W., Ting, Y.-S., et al. 2017, MNRAS, 473, 5043
Feroz, F., Hobson, M. P., & Bridges, M. 2009, MNRAS, 398, 1601
Ferruit, P., Bagnasco, G., Bartho, R., et al. 2012, Proc. SPIE, 8442, 84422O
Gaudi, B. S., Seager, S., Mennesson, B., et al. 2020, arXiv:2001.06683
Harrington, J., Hansen, B. M., Luszcz, S. H., et al. 2006, Sci, 314, 623
Keating, D., Cowan, N. B., & Dang, L. 2019, NatAs, 3, 1092
Kendrew, S., Dicken, D., Bouwman, J., et al. 2018, Proc. SPIE, 10698, 106983U
Knutson, H. A., Lewis, N., Fortney, J. J., et al. 2012, ApJ, 754, 22
Kopparapu, R. k., Wolf, E. T., Arney, G., et al. 2017, ApJ, 845, 5
Kreidberg, L., Koll, D. B. B., Morley, C., et al. 2019, Natur, 573, 87
Krick, J. E., Ingalls, J., Carey, S., et al. 2016, ApJ, 824, 27
Mansfield, M., Bean, J. L., Stevenson, K. B., et al. 2020, ApJL, 888, L15
Maxted, P. F. L., Anderson, D. R., Doyle, A. P., et al. 2013, MNRAS, 428, 2645
Meixner, M., Cooray, A., Leisawitz, D., et al. 2019, arXiv:1912.06213
Mullally, S. E., Rodriguez, D. R., Stevenson, K. B., & Wakeford, H. R. 2019, RNAAS, 3, 193
National Academies of Sciences, E. & Medicine 2018, Exoplanet Science Strategy (Washington, DC: The National Academies Press)
National Academies of Sciences, E. & Medicine 2019, An Astrobiology Strategy for the Search for Life in the Universe (Washington, DC: The National Academies Press)

Figure A2. Same as Figure A1, except using JWST’s MIRI/LRS instrument mode. In this case, we are unable to resolve the planet’s radius–temperature degeneracy, thus leading to large uncertainties in both parameters.
Seager, S., & Deming, D. 2009, ApJ, 703, 1884
Seifahrt, A., Stürmer, J., Bean, J. L., & Schwab, C. 2018, Proc. SPIE, 10702, 107026D
Selsis, F., Wordsworth, R. D., & Forget, F. 2011, A&A, 532, A1
Skilling, J. 2004, in AIP Conf. Ser. 735, Bayesian Inference and Maximum Entropy Methods in Science and Engineering, ed. R. Fischer, R. Preuss, & U. V. Toussaint (Melville, NY: AIP), 395
Skilling, J. 2006, BayAn, 1, 833
Speagle, J. S. 2020, MNRAS, 493, 3132
Staguhn, J., Mandell, A., Stevenson, K., et al. 2019, arXiv:1908.02356
Stevenson, K. B., Line, M. R., Bean, J. L., et al. 2017, AJ, 153, 68
The LUVOIR Team 2019, arXiv:1912.06219
Wakeford, H. R., Lewis, N. K., Fowler, J., et al. 2019, AJ, 157, 11
Werner, M. W., et al. 2004, ApJS, 154, 1