Exoplanet Science with SPHEREx's All-Sky Spectro-photometric Survey in the Near-Infrared

A White Paper in support of the Exoplanet Science Strategy

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Introduction. SPHEREx, the Spectro-Photometer for the History of the Universe, Epoch of Reionization and Ices Explorer, is a mission proposed to NASA's competed Explorer program, currently in Phase A formulation as a Medium-sized Explorer (MIDEX), with downselect scheduled for late calendar year 2018. SPHEREx aims to carry out an all-sky spectrophotometric survey in 96 narrow bands spanning 0.75 to 5 microns, at 6" resolution to a depth of approximately 18th [Vega] magnitude in J band. Following launch, planned for 2023, SPHEREx will conduct four all-sky surveys during its baseline 2-year mission. SPHEREx is focused on three science themes (Inflationary Cosmology, Galaxy Formation, and Galactic Ices), but also provides powerful data sets for many fields across astronomy: first, with the all-sky survey allowing statistical studies of populations of objects, and secondly with spectrophotometry across an under-sampled wavelength range that is more easily accessible from space. See spherex.caltech.edu for additional information about the mission.

SPHEREx and Exoplanets. SPHEREx, often in tandem with other NASA and ESA missions, offers many opportunities for the study of exoplanets and exoplanet systems in all evolutionary stages. Most notably, SPHEREx and *Gaia* together will provide greatly improved knowledge of transiting planets' host stars, leading in turn to much more precise measurements of exoplanet radii [and densities, when masses are available]. In addition, SPHEREx can characterize warm dust around main sequence stars which may signal the occurrence of cataclysmic events similar to those thought to have occurred in the early Solar System. Finally, SPHEREx' studies of icy grains around young and forming stars may help us to understand how ices evolve in planet-forming systems.

Improved Knowledge of Exoplanet Host Stars. The transit and radial velocity (RV) exoplanet detection techniques have led to the discovery of thousands of exoplanets (approximately 3,500 according to the NASA Exoplanet Archive as of 26 Feb 2018), and upcoming surveys such as the Transiting Exoplanets Survey Satellite (TESS) are expected to find thousands more (Sullivan et al. 2015). Since these are indirect detection methods, the masses and radii -- and the precision and accuracy thereof -- measured for exoplanets discovered with these methods depend directly on precise and accurate characterization of their host stars.

For example, knowledge of a rocky planet's measured bulk density alone is insufficient to uniquely constrain its interior composition, so planetary interior models often use stellar elemental abundances, such as the silicon-to-iron ratio, to further constrain the planet's composition. Empirical measurements of the star-planet [Si/Fe] correlation can improve the accuracy of these models, but such measurements require percent-level planetary radius and mass measurements (Wolfgang & Fortney 2018). These requirements necessitate percent-level precision for the stellar parameters. While low-mass stars such as M dwarfs provide the best opportunities for finding small, rocky planets – for a given planet, a smaller, less massive star yields larger radius and mass ratios and thus larger transit and RV signals – current models are discrepant at the few-to-several percent level with observations.

Stevens, Gaudi, & Stassun (2018, in review) and Beatty et al. (2017) argue that precise and accurate stellar and planetary parameters will soon be measurable by a joint analysis of transit photometry, RVs, stellar broad-band flux measurements, and ultra-precise *Gaia* parallaxes. For a typical TESS target with $8 \leq V \leq 11$, a wealth of broad-band photometry exists in the literature from the UV (GALEX) to the IR (WISE). However, for dwarfs with spectral types M through A, only 40-70% of the flux is captured in these measurements. This type of analysis therefore requires the use of model atmospheres to infer the stellar bolometric flux from the spectral energy distribution (SED). The bolometric flux, combined with a parallax, provides the stellar radius; the radius and the stellar density measured from the transit yield the stellar mass; the radius and the transit depth give the planet radius; and the stellar mass and RV orbit give the planet mass. In this case, the precision and accuracy of the inferred stellar and planetary properties hinge on the precision and accuracy of not only transit photometry and RVs, but also of stellar atmosphere models.

Starting in April 2018, publicly available *Gaia* data will provide, in addition to parallaxes, low-resolution spectrophotometry from 330-1050 nm, covering the stellar spectral energy distribution (SED) peak for the earlier spectral types. SPHEREx's VIS-near-IR spectrophotometry between 0.75 − 5.0 µm would cover the SED peak for mid-K and later spectral types, as well as the Rayleigh-Jeans tail of all observed stars. Adding these measurements to the existing flux measurements then captures 90-98% of the total stellar flux for these spectral types, enabling bolometric flux determinations that are either *independent of* or only weakly dependent on model atmospheres.

Spectral Type & Magnitude	Parameter	Value, Uncertainty, & Fractional Precision		
		Broadband Photometry Only	Broadband & *Gaia* Photometry	Broadband, *Gaia*, & SPHEREx Photometry
F Dwarf ($V \sim 10$)	T_{eff} (K)	6300 $\pm$ 100 (2%)	6290 $\pm$ 50 (0.8%)	6265 $\pm$ 15 (0.2%)
	F_{bol} (erg/s/cm^2)	$3\times10^{-9} \pm 10^{-10}$ (3%)	$3\times10^{-9} \pm 5\times10^{-11}$ (2%)	$3\times10^{-9} \pm 2\times10^{-11}$ (0.6%)
	R_* (R_{Sun})	1.59 $\pm$ 0.04 (2%)	1.62 $\pm$ 0.02 (1%)	1.589 $\pm$ 0.005 (0.3%)
M Dwarf ($V \sim 16$)	T_{eff} (K)	3900 $\pm$ 50 (1%)	3888 $\pm$ 25 (0.6%)	3912 $\pm$ 8 (0.2%)
	F_{bol} (erg/s/cm^2)	$5\times10^{-11} \pm 2\times10^{-12}$ (4%)	$5\times10^{-11} \pm 9\times10^{-13}$ (2%)	$4\times10^{-11} \pm 3\times10^{-13}$ (0.8%)
	R_* (R_{Sun})	0.58 $\pm$ 0.03 (5%)	0.582 $\pm$ 0.014 (2%)	0.570 $\pm$ 0.005 (0.9%)

Table 1: Precision on the stellar effective temperature T_{eff}, bolometric flux F_{bol}, and radius R_* inferred from SED modeling of two planet-host stars: an F dwarf (KELT-3; Pepper et al. 2013), and an M dwarf (NGTS-1; Bayliss et al. 2018). From left to right, the columns show results for an SED fit to extant broadband photometry only, broadband photometry combined with Gaia spectrophotometry, and broadband photometry combined with both Gaia and SPHEREx spectrophotometry. In each case, a precise distance determination from Gaia is assumed.

Table 1 shows how, for two representative stars, combining SPHEREx and *Gaia* spectrophotometry can improve the precision of the SED-derived stellar parameters over fitting to the broad-band photometry alone. By measuring nearly all the stellar flux, effective temperatures can be inferred to <10 K (<1%) precision. Likewise, stellar radii can be determined to <1% precision, a level comparable to that achieved with interferometric techniques, but this method is applicable to stars hundreds of parsecs away. Figure 1 illustrates the power of this stellar radius constraint – both in terms of the radius precision itself and how this constraint complements the high-precision density constraints achievable with short-cadence observations from TESS. Note that the broad wavelength coverage of the *Gaia*-SPHEREx data set also allows determination of and correction for interstellar reddening even for extinction as low as Av ~ 0.05, which further improves the precision of the determination of stellar parameters. With the stellar parameters so well-determined, those of the transiting planet will be limited only by the uncertainties in the transit and stellar RV measurements.

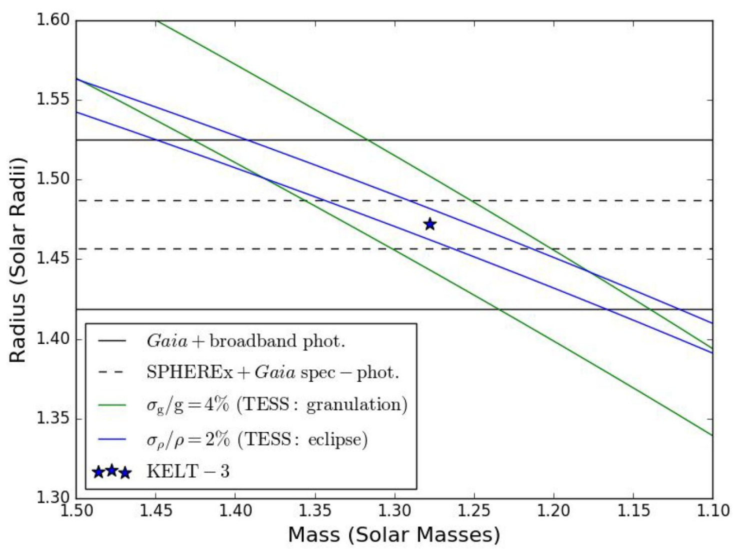

Figure 1: Estimated mass and radius constraints on the transiting hot Jupiter host KELT-3. The star denotes the mass and radius values from Pepper et al. (2013). The constraint from a 4% surface gravity inferred from granulation-driven flux variations observable with TESS' short-cadence photometry (e.g. Kallinger et al. 2016) is shown in green, while a 2% stellar density constraint from TESS transit observations at the short cadence is shown in blue. The radius constraint from SED modeling using only broad-band flux measurements and a Gaia *parallax with 7 micro-arcsecond uncertainty is shown by the black solid lines, while the more precise constraint achieved by incorporating SPHEREx and* Gaia *spectrophotometry is shown by the dashed black lines.*

TESS will provide high-quality transit data for ~1,700 planets, of which ~550 are expected to be Earths and Super-Earths. *Gaia* and SPHEREx will produce an all-sky archive which will be available to characterize not only all TESS exoplanet host stars but also almost all identified in the future from both ground and space observatories. For example, ESA's PLAnetary Transits and Occultations (PLATO) satellite – to be launched in 2026 - is expected to characterize ~4,800

V < 13 transiting systems precisely, targeting longer-period systems to search for Earth-like planets in the habitable zones of Sun-like stars, of which it is expected to find ~60 (ESA 2017). Like TESS PLATO will concentrate on bright stars readily measured by SPHEREx and *Gaia*. With the abundance of high-precision stellar densities from the transit and asteroseismology measurements from these satellites, SPHEREx and *Gaia* have the potential to improve our knowledge of thousands of stellar and planetary radii and masses, ushering in an area of high precision exoplanet studies.

Dust Around Main Sequence Stars. The collisional process that creates planets leaves behind debris in the form of planetesimals and dust (extrasolar analogs of asteroids and comets on the one hand and the zodiacal and Kuiper Belt dust on the other). The dust, heated by the star and replenished from the planetesimals, can frequently be observed, and studies of these debris disks has proven to be a powerful means of probing the underlying exoplanetary systems. Debris disk studies have concentrated on wavelengths longward of 10 µm because the disks generally appear to contain dust no warmer than 300K and because the contrast relative to the stellar photosphere increases with wavelength.

Recent Spitzer observations of extreme debris disks at 3.6 and 4.5 µm have returned striking results which SPHEREx will build upon. Extreme debris disks are systems with $L_{dust}/L_{Star} \geq 0.01$, 0.01, about two orders of magnitude greater than what had previously considered to be a bright debris disk. The brightness of the debris disk simply reflects the amount of dust orbiting the star, so these systems are unusual in having both a large amount of circumstellar dust and having dust warm enough to radiate significantly shortward of 5 µm. Several such disks have been identified orbiting stars younger than ~200 Myr, and found to have one other unusual property, which is that their infrared radiation shows marked variability on time scales of months to years (Meng et al. 2014, 2015).

These extreme debris disks vary much more rapidly than predicted for evolutionary models in which the dust in debris disks result from a gradual collisional cascade. For the case of ID8 in NGC2547, for example, Meng et al suggest that the variability results from a major collision between two large (100--1000 km radii) bodies of which some material might be vaporized, and then recondense rapidly into sand-szied particles. Those particles would subsequently be degraded by collisions into the particles seen in the infrared, which are blown out of the system. Truly titanic collisions may be needed to produce the dust clouds required to account for the variability of the extreme debris disks. Several such collisions are thought to have taken place in the first 100 Myr of our Solar System, and others may have been triggered in tandem with the Late Heavy Bombardment which caused comets and asteroids to rain down on the terrestrial planets when the Solar System was 600 to 800 Myr old.

SPHEREx can discover systems of this type, in which the dust emission rises above the stellar photosphere at 3 µm, and the six-month cadence of SPHEREx surveys is well-matched to the variability timescale of these extreme systems. Particularly interesting candidates will be identified for JWST followup, while SPHEREx refines our understanding of the statistics of their occurrences and the attribution to the types of collisions described above. The SPHEREx census will reveal the importance and frequency of such violent events in the early stages of planet formation, and determine whether our own Solar System has a typical history, or if instead it stands out as an unusual system in the Milky Way.

Ices and Planet Formation. Ices are an important yet relatively unexplored component of the interstellar medium and planet forming disks. Fewer than 250 ice absorption spectra have been obtained to date from the Infrared Space Observatory, Spitzer, and AKARI. Nevertheless, based on these data and gas-phase water data from the Submillimeter Wave Astronomy Satellite and Herschel, it's now clear that 99% or more of the water in dense clouds is locked in ice. Along with organic molecules, ice-covered dust grains are predicted to be major repositories of the ingredients of life, and their inclusion in larger bodies formed in protoplanetary disks may be key to understanding how life can arise on habitable worlds. Constraining ice column densities is key to modeling planet formation because the snow lines for different molecular species strongly affect the initial conditions for a model (Qi et al, 2013). SPHEREx's statistically significant study of ices across a broad range of source types, including the quantity (i.e., column density) of each ice species as well as chemical changes within the ice, will be a major contribution to the study of the origins of exoplanet composition.

Within SPHEREx's wavelength range lie a number of important biogenic ice features, including that of H_2O (3.05 µm), CO_2 (4.27 µm), $^{13}CO_2$ (4.38 µm), XCN (4.62 µm), CO (4.67 µm), and OCS (4.91 µm). During each of its four baseline all-sky surveys, it's expected that SPHEREx will obtain absorption spectra toward more than 10^5, and possibly as many as 2×10^6, Milky Way sources spanning a broad range of evolutionary stages from diffuse and dense clouds to young stellar objects and protoplanetary disks. The diversity of objects observed coupled with the large number of sources for which high signal-to-noise spectra will be obtained will allow SPHEREx to trace the formation, growth, and chemical changes, if any, of these biologically important ices through these evolutionary stages to newly forming planets. Doing so will not only allow SPHEREx to determine the column densities and relative abundances of these ices in protoplanetary disks, but also determine whether these ices are delivered unaltered from their progenitor clouds or whether they undergo significant chemical changes within these disks.

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