Formation, Detection, and Characterization of Extrasolar Habitable Planets
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Occultation Spectrophotometry of Extrasolar Planets with SOFIA

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Abstract. The NASA/DLR Stratospheric Observatory for Infrared Astronomy (SOFIA), a 2.5-meter infrared telescope on board a Boeing 747-SP, will conduct 0.3 - 1,600 μm photometric, spectroscopic, and imaging observations from altitudes as high as 45,000 ft., where the average atmospheric transmission is greater than 80 percent. SOFIA's first light cameras and spectrometers, as well as future generations of instruments, will make important contributions to the characterization of the physical properties of exoplanets. Our analysis shows that optical and near-infrared photometric and spectrophotometric follow-up observations during planetary transits and eclipses will be feasible with SOFIA's instrumentation, in particular the HIPO-FLITECAM optical/NIR instruments. The airborne-based platform has unique advantages in comparison to ground- and space-based observatories in this field of research which we will outline here. Furthermore we will present two exemplary science cases, that will be conducted in SOFIA's cycle 1.

Keywords. SOFIA, exoplanets, transit, eclipse, spectrophotometry

1. Overview: SOFIA

The Stratospheric Observatory for Infrared Astronomy (SOFIA), a joint project of NASA and the German Aerospace Center (DLR), is a 2.5-m telescope on board a Boeing 747-SP aircraft. It is designed to perform sensitive astronomical measurements between 0.3 μ and 1.6 mm, flying as high as 45,000 feet (13.72 km), above 99.8% of the obscuring atmospheric H_2O vapor (Gehrz *et al.* 2010). The home base for the SOFIA aircraft is NASA's Dryden Aircraft Operations Facility in Palmdale, CA. SOFIA will also operate from other bases worldwide to enable observations at any declination and to facilitate timely observations of transient events, including planetary occulations and extrasolar planet transits. The telescope combines a 2.7 m (2.5 m effective aperture) parabolic primary mirror with a 0.35 m diameter hyperbolic secondary mirror. The scientific instruments operate at a f/19.6 Nasmyth infrared focus fed by a 45-degree dichroic tertiary mirror that transmits the optical light. A flat behind the dichroic feeds the visible light into an optical focal plane guiding camera system, the Focal Plane Imager (FPI), at a second Nasmyth focus. Three other independent imaging and guiding cameras are available: the Wide Field Imager (WFI), the Fast Diagnostic Camera (FDC) and the Fine Field Imager (FFI). The dichroic tertiary can be replaced by a fully reflecting tertiary for applications requiring maximum throughput at these short wavelengths.

SOFIA's first generation science instruments include high speed photometers, imaging cameras, and spectrographs capable of resolving both broad features due to dust and large molecules, and molecular and atomic gas lines at km/s resolution. SOFIA can rapidly incorporate instrumentation upgrades in response to new technological developments.

Science observations began in 2010 (first light flight: May 10, 2010) and full science operations are expected to continue for another twenty years. Detailed descriptions of the scientific and operational advantages of the SOFIA observatory, its development and deployment schedule, and opportunities for participation by observers and instrument developers are described in Becklin & Gehrz (2009) and Gehrz *et al.* (2009).

2. Exoplanet Observations with SOFIA

In the last few years, the characterization of exoplanet atmospheres using observations from the Hubble and Spitzer Space Telescopes has led to an 'Era of Comparative Exoplanetology' initiated by the first detections of light emitted by an exoplanet (e.g. Charbonneau *et al.* 2005; Deming *et al.* 2005), the first spectrum of an exoplanet (Richardson *et al.* 2007; Grillmair *et al.* 2007), and the first phase curve for an exoplanet (Knutson *et al.* 2007a). By utilizing the transit method (measuring the small, wavelength-dependent variation in flux as an exoplanet passes in front of or behind its parent star), we are now able to detect hazes in an exoplanetary atmosphere (Pont *et al.* 2008) and measure abundances of H_2O, CH_4, CO, and CO_2 in several exoplanetary atmospheres (Grillmair *et al.* 2008; Swain *et al.* 2009a; Swain *et al.* 2009b; Madhusudhan & Seager 2009). However, due to its Earth-trailing orbit, Spitzer will inevitably become unavailable for further observations in 2013 and is only capable of photometric observations in limited bandpasses in its warm mission phase. Hubble may maintain operations until ~2020, but the current instrumentation limits Hubble to wavelengths shorter than 1.7 μm. The crucial challenge in this field today is to overcome these limitations prior to the launch of the James Webb Space Telescope (JWST). In particular, ground-based spectrophotometry of transits and eclipses of extrasolar planets suffer from inconsistent or highly disputed results (e.g., Swain *et al.* 2010). Observations in the near-IR (NIR) – where the planet's emission peaks and the photo-chemistry of the atmospheric molecules is imprinted onto the emission and transmission spectra – are significantly affected by the perturbing variations of trace gases in the Earth's atmosphere. These molecular species are the exact same as the species of interest in the exo-atmospheres. For example, Angerhausen (2010), 2.7.1) showed that their spectrophotometric precision was limited by telluric systematics, with variable transmission of up to 0.05 in deep CO_2 absorption bands and 0.005-0.01 in other H_20 and CH_4 K-band features for an average night at the Very Large Telescope site in Chile.

In space, observatories can observe exoplanets without the obscuring telluric effects. Recently Hubble and Spitzer have been successfully used for spectroscopic characterization of extrasolar planets. But as the warm Spitzer mission phase winds down and the Hubble IR-instrumentation is limited, high precision NIR observations beyond 1.7 μm that access important atmospheric diagnostics are limited until JWST begins science operations in 2019 (launch approx. October 2018). In the near-future, surveys from ground-based facilities and the CoRoT and Kepler spacecraft will deliver a large number of new targets with interesting opportunities for characterization. The airborne observatory SOFIA will play a key role in spectroscopic characterization of these planets and will serve as testbed for future JWST observations (Fig. 1).

2.1. *Advantages for occultation spectrophotometry*

SOFIA has a specific and unique phase space for extremely precise time-domain spectrophotometric observations at IR wavelengths:

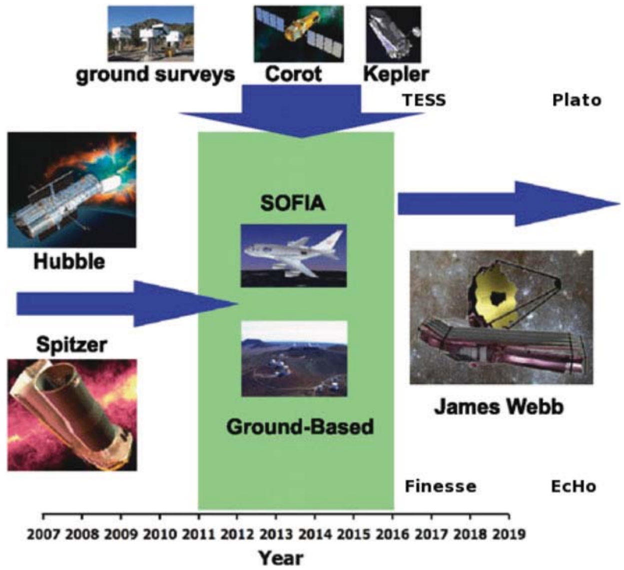

Figure 1. Exoplanet occultation spectrophotometry in the next decade: In the past few years Hubble and Spitzer (left) have been successfully used for spectroscopic characterization of extrasolar planets. As warm Spitzer winds down and Hubble's infrared capabilities are restricted to wavelengths below 1.7 μm, space-based opportunities are limited until JWST (and possibly, if selected FINESSE, EcHo) starts operating. Over the next several years ground-based surveys (such as MEarth, HATNet or KELT) and space-based missions (such as WASP, CoRoT or Kepler and TESS/Plato in the future) (top) will continue to deliver a large number of new targets with interesting opportunities for characterization. The airborne observatory SOFIA will allow follow-up observations of these planets as a testbed for observational strategies and target decision guidance for future observations with (dedicated) space-borne platforms.

It operates in important wavelength regimes, where the planet's black-body temperature peaks and contrast ratios between the star and planet improve. Furthermore many important atmospheric properties, such as the chemical constituents or the temperature-pressure profiles of planets, can be analyzed with IR spectra, observed during transits or eclipses of the planet.

The variability of Earth's atmospheric transmission and emission as well as the temporal variability of its constituents is the most crucial challenge in ground-based transit observations, in particular when it comes to the spectroscopic analysis of molecular features in the exoplanet's atmosphere that are also present as telluric trace gases (Fig. 2). Again, SOFIA will also be more favorable with these effects since it will be able to fly high enough to be independent of near surface processes affecting the H_2O, CH_4, and other diagnostic lines.

The SOFIA telescope operates at much lower temperatures (240 K) than ground-based telescopes. Therefore thermal background contributions, that are the dominant noise source for transit observations at wavelengths longer than 3 micron, will be significantly reduced.

SOFIA can observe time-critical events, such as the rare transits of long-period planets, under optimized conditions. This was recently demonstrated by the PIs of HIPO, the Fast Diagnostic Camera (FDC) and SOFIA team in an observation of a Pluto occultation in June 2011 (Dunham *et al.* 2012). For short-period close-in transiting planets with transits and eclipses occurring every 2-5 days, the optimal observing schedules for ground-based transit observations are reduced to only a few nights per year for a given observing site

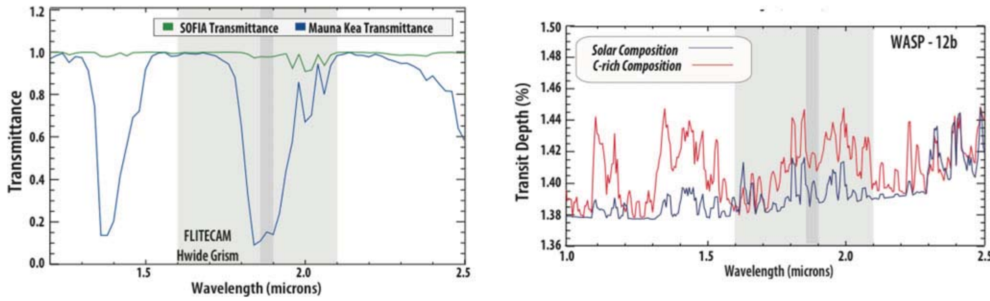

Figure 2. Left: Transmittance of Earths atmosphere between 1.2 and 2.5 μm, illustrating the importance of SOFIA for this wavelength regime. The NIR H_2O bands become almost opaque and highly variable at even the best observing sites from the ground, but are nearly transparent at SOFIA altitudes. Our FLITECAM observations will probe this region directly. Right: Model transit spectra of WASP-12 b with two different carbon-to-oxygen ratios. The different compositions lead to very different depths in the H-band, which FLITCAM will probe directly.

as the event is best observed close to target culmination and local midnight. Hubble, on the other hand, is able to observe transits at many more opportunities but is in most cases limited to series of 96 minute on/off-target batches due to its low-earth orbit. These limitations of ground- and space-based platforms present a substantial hurdle – particularly for transiting planets with very long orbits (such as HD80606b) and therefore transit durations of more than 6 hours. The analysis of potential flight schedules shows that the mobile platform SOFIA will be able to take off close to the optimal geographic location for each of those events. The airborne observatory will be able to observe the complete event continuously and with a very stable setup (telescope elevation, airmass, etc.) during observing flights of up to 10 hours duration.

Until the start of the JWST mission and after the end of warm Spitzer (2013), SOFIA will be the only (airborne) platform capable of NIR spectrophotometry of exoplanet atmospheres beyond 1.7 μm (Hubble's longest wavelength after the last servicing mission) at an altitude where the impact of variable telluric absorption is small enough for high precision observations of the same molecules also present in the exoplanetary atmosphere (see Fig. 1).

2.2. *Example science cases*

In this section we present two successful cycle 1 proposals as exemplary science cases for SOFIA in the field of exoplanet characterization. These observations will not only allow us to conduct ground-breaking science, but will enable us to characterize both spectroscopic and photometric observing modes for high-precision time series analysis, paving the way for future observations of a wide range of exoplanet atmospheres with SOFIA's first generation instruments.

2.2.1. *Characterizing Transiting Exoplanets Using FLITECAM: An Exploratory Program*

We will explore SOFIA's exoplanet characterization capability by conducting observations of two transiting exoplanets using the spectroscopy mode of FLITECAM. Our two exoplanet targets, HD189733 b and WASP-12 b, are proposed for their potential to aid in characterizing the spectrophotometric precision of FLITECAM in addition to the intrinsic scientific questions that we hope to answer regarding their atmospheres. HD189733 b is a Jupiter-mass planet orbiting at 0.03 AU around one of the closest K-type stars; the deep transit signal in addition to a very high flux from the host star results in the best opportunity for high-precision characterization of any known exoplanet. This transiting system is the gold standard for exoplanet observations and has been the target for many ground- and space-based observations. Both multi-band photometry and spectroscopy with Spitzer have provided measurements of the mid-IR emission from the planet by measuring the occultation of the planet by the central star, probing molecular absorption and the temperature structure in the bulk of the upper atmosphere (e.g., Grillmair *et al.* 2008). Observations with Hubble have explored molecular bands in the NIR, and indeed, early results with the NICMOS spectrograph claimed absorption from H_2O, CH_4 and CO_2 between 1.5 and 2.5 μm (Swain *et al.* 2008). However, these features have been irreproducible with alternate analysis techniques and it is still uncertain whether these molecular features exist or if there is a haze that obscures wavelengths below 2 μm (Gibson *et al.* 2011, Pont *et al.* 2008). SOFIA/FLITECAM observations will probe this same spectral region, and these observations will be able to confirm or reject the existence of the putative absorbers (Fig. 2).

SOFIA observations of the exoplanet WASP-12 b also present an opportunity to resolve uncertainty surrounding its atmospheric composition. WASP-12 is a dimmer target than HD189733, but it may host the first planet discovered to have a C/O ratio greater than 1 (Madhusudhan *et al.* 2011), suggesting a carbon-rich atmosphere and a very different thermochemical environment than we see in our own Solar System. A ratio of C/O > 1 will lead to weak H_2O absorption in the atmosphere since all the oxygen will be bound up in CO. SOFIA/FLITECAM is the only instrument that can probe many of the NIR molecular bands beyond 1.7 μm at high precision (Fig. 2), and therefore has the opportunity to provide unique insight into this unusual object.

These two exoplanet targets present scientifically compelling cases for preliminary observations, while also providing a balanced observing program for cycle 1. HD189733 is extremely bright, and therefore offers the best S/N but also the chance to test FLITECAM's ability to observe bright targets, including the effects of detector persistence and the impact of extremely short exposure times. WASP-12 is less bright and is available for observation at a different time of year from HD189733. Both planets have very short orbital periods – HD189733 b has a period of 2.2 days, while WASP-12 b has a period of 1.1 days – and relatively lengthy transit durations (1.8 hours for HD189733 and $\sim$3 hours for WASP-12), and therefore provide many observing opportunities and flexibility in planning the SOFIA observing schedule.

This program will determine the best observational methodology for exoplanet transit measurements by testing the spectrophotometric precision of FLITECAM. Grism spectroscopy clearly provides the most direct path to continual spectral coverage across specific spectral bands of interest, and the current filter and grism sets available with FLITECAM will allow us to simultaneously probe a number of molecular bands in the NIR. Due to telluric absorption in our own atmosphere, astrophysical measurements of these molecular bands are extremely difficult form the ground since they are almost completely obscured by absorption in our own atmosphere, and SOFIA provides a unique capability at these wavelengths. However, the ability to adequately calibrate and control for instrumental and atmospheric variability during spectroscopic observations with FLITECAM spanning approximately 2 hours is currently unknown. Several important factors have been accounted for, including the image motion due to mechanical vibrations and turbulence across the telescope cavity as well as the magnitude and variability of sky emission and absorption over multi-hour timescales at stratospheric altitudes. Using a traditional spectrograph with a slit width equivalent to the expected SOFIA FWHM and the most optimistic pointing stability, the variable slit losses would likely lead to an uncertainty of 0.5% in the final photometric time series (Knutson *et al.* 2007b); though these errors could be corrected somewhat through PSF modeling and decorrelation techniques, the final photometric stability would be insufficient to meet our science goals. To mitigate these problems, we will use the grism mode of FLITECAM but without the slit. This strategy will clearly result in increased background levels at even the shortest wavelengths, but considering the brightness of our target stars, the noise due to sky background will be minor compared to the photon noise. These stars both have bright reference stars that also fall within the FLITECAM $8' \times 8'$ field of view, and we will therefore be able to measure simultaneous reference spectra for all bright objects in the field.

2.2.2. *Do starspots inflate the exoplanet CoRoT-2b?*

The measurement of planetary densities is important for the characterization of exoplanets because it can be used to estimate their structure and chemical composition. However, determining precise densities is difficult for several reasons. Fundamental parameters of a planet, such as radius, mass, density, and temperature, are only as precise as the accuracy to which the parameters of the host star are known. Estimates of stellar radii usually have uncertainties of several percent, which enter the error of planetary densities by a power of three. Another effect influencing the errors of planetary radii is stellar activity. Most stars in our Galaxy are of low mass and show surface activity such as flares and starspots. Starspots especially can lead to systematic errors in the determination of planetary radii from transit lightcurves (Czesla *et al.* 2009): starspots affect the relative depths of transits which, if not considered in the analysis of high-precision lightcurves, can result in incorrect values of the radius – again with errors of up to several percent for highly active stars.

Indeed, the observed radii of several exoplanets significantly exceed model predictions (e.g. Gillon *et al.* 2009, Fortney *et al.* 2011, Faedi *et al.* 2011); one extreme case is CoRoT-2b with a radius inflated by about 30 % (Guillot & Havel (2011)). This hot-Jupiter orbits the young, solar-type, very active star CoRoT-2A, which was observed (in the optical) by the CoRoT satellite for half a year (Alonso *et al.* 2008). A visual inspection of the lightcurve immediately shows the star's high level of activity: the rotational modulation due to large starspots induces peak-to-peak variations of 6 % with a period of 4.5 days. Analyzing the 79 observed transits of CoRoT-2b, Huber *et al.* (2010) could show that virtually all transits are deformed by starspots and the undisturbed 'true' transit profile is never observed. Modeling of the CoRoT-2A lightcurve by (Huber *et al.* 2009, 2010) provides evidence that about 20 % of the stellar surface is covered with starspots. Such high coverage fractions significantly affect the estimate of the planetary radius and could explain a substantial part of the observed inflation.

The effects of starspots on lightcurves are wavelength-dependent. Observations of CoRoT-2b's transits in the infrared should be much less affected by starspots than the CoRoT lightcurve. However, the analysis of starspots requires a lightcurve quality much higher than currently available from the ground. Only SOFIA's unique capability of obtaining a space-based quality, short-cadence, infrared transit lightcurve of CoRoT-2b can pin down its real radius almost unaffected by starspots. Furthermore, it can deliver these high-quality observations in several photometric bands *simultaneously* when using the instruments HIPO and FLITECAM together. This multi-band photometry will allow us to measure the correct size of CoRoT-2b and, thus, gives much better constraints on its density and chemical composition; it will also allow us to directly measure the temperature of spots on the solar-like star CoRoT-2A with unprecedented accuracy.

Starspots alone might not be able to explain CoRoT-2b's large radius entirely. Several other factors might contribute to the blown up radius as well: the planet's close proximity to the star leads to an enormously heated surface and Schroeter *et al.* (2011) show that CoRoT-2A immerses its planet in an intense high-energy radiation field ($L_X \sim 10^{29}$ erg/s). The SOFIA observations will have the precision to determine the true radius of the planet and, if they confirm the radius anomaly, will be an important input for all evolutionary studies and atmosphere models of young hot-Jupiters.

3. Summary

We demonstrate that SOFIA has a specific and unique phase space for exoplanet research in the next decade. SOFIA operates in the right wavelength regime, above most of the perturbing variation of atmospheric trace gases and can observe rare transient events under optimized conditions. SOFIA will immediately be a competitive observatory for state-of-the-art exoplanet astronomy with some aspects exclusive to SOFIA until the JWST era.

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