Determining the Composition of super-Earth and sub-Neptune Exoplanets.

Objective: Measure the masses of small, cool planets discovered by NASA's *K2* and *TESS* missions, in order to constrain planet masses, densities, compositions, to test planet formation theories, and to prepare for observations of these planets with the upcoming *JWST* mission.

Motivation: The field of exoplanets has shifted from detection to characterization over the last few years due to technological improvements in instrumentation and large detection surveys such as NASA's *Kepler* mission. One of the most surprising results from *Kepler* was the prevalence of planets between 1 — 4 earth-radii ($R_\oplus$), called "super-Earths" or "sub-Neptunes", which are absent from our solar system (Howard et al. 2012; Fressin et al. 2013). Their formation is a mystery; they do not fit within the "core accretion" models that predict a few-earth mass sized core would trigger runaway gas accretion and form into a gas giant (Mizuno 1980; Bodenheimer & Lissauer 2014). It is also debated whether there is sufficient material in the inner protoplanetary disk to form these planets (Weidenschilling 1977; Hayashi 1981).

Planet compositions and temperatures provide a crucial link to their formation histories; formation models depend on planet composition which can be inferred from their bulk densities. To determine the bulk density, the radius and mass of a planet are needed. The transit method is used to measure the radius. A transiting planet passes in front of its host star which causes the measured starlight to decrease proportionally to the planet's size. The mass is commonly measured using the radial velocity (RV) method (Mayor & Queloz 1995) where spectrographs are used to measure the reflex motion of stars caused by the gravitational pull of orbiting planets. By combining the transit radius with the RV mass, we can compute bulk density and infer planetary composition. Kepler transits and ground-based RV discovered an increase in bulk density with decreasing size, suggesting a transition region at 1.5 — 2.0 $R_\oplus$ between volatile-rich gas/ice planets and rocky planets (Weiss & Marcy 2014; Rogers 2015). However, most of the previously characterized planets were hot ($>$ 800K), so many have been sculpted by atmospheric mass loss. Furthermore, a larger sample of small planet densities are needed to examine this transition region and to constrain related formation theories.

I will measure the mass/radius relation and probe the diversity of compositions for planets between 1-2 $R_\oplus$, cooler than 800 K, from two NASA missions: *K2* and the Transiting Exoplanet Survey Satellite (*TESS*). I will collect RV mass measurements from the Automated Planet Finder's (APF) Levy Spectrograph and the High Resolution Echelle Spectrometer (HIRES) on Keck. As a UCSC graduate student, I have considerable access to these proven, high-precision instruments which are essential to the success of my project. The combination of RV mass and transit radius will reveal the intrinsic distribution of planet mass and radius, and will constrain planet compositions. **Furthermore, these new measured masses and densities will help prioritize planets for atmospheric characterization by transmission spectroscopy using the Hubble Space Telescope (*HST*) and James Webb Space Telescope (*JWST*).**

K2 is providing a larger sample of cool planets orbiting bright stars (Howell et al. 2014; Crossfield et al. 2016) than *Kepler*, and *TESS* will find even brighter systems around nearby stars (Ricker et al. 2014; Sullivan et al 2015). These bright host stars can be more precisely followed up with RV. Mass measurements of small planets have been limited because the majority discovered by *Kepler* orbit faint stars. Furthermore, most of the known planets have an equilibrium temperature greater than 800 K, indicating atmospheric escape may have caused high mass loss. These planets will have a different mass-radius relationship; therefore, formation models based on parameters derived from these hot planets may be inaccurate. By determining the mass-radius relationship for cooler planets, I will also be able to constrain atmospheric evolution models by comparing to the sample of hotter planets.

My Approach: I propose to measure the masses of small planets using RVs from Keck and APF. I am working with a large collaboration led by my advisor, Dr. Ian Crossfield, to characterize transiting planets observed by NASA's *K2* mission; I have begun the analysis of this sample, as described below. My RV survey will probe the diversity of sub-Neptune planet masses and densities at a wider range of planet temperatures and orbital configurations than was possible from the *Kepler* planet sample. Our team observes on dozens of nights each semester with Keck and has access to 80% of all APF time through my collaborators Vogt (UCSC) and Howard (Caltech). The high cadence and continuous coverage necessary to disentangle low-amplitude planetary signals from stellar activity (Howard et al. 2013; Anglada-Escudé et al. 2016) is only possible through my extensive access to APF. In the final year of my fellowship, the Keck Planet Finder (KPF) will come online and dramatically increase my survey sensitivity (Gibson et al. 2016). My access to these world-class telescopes and experienced collaborators will enable me to complete this RV program.

Two interesting, early examples of such systems from *K2* are K2-3 and HD106315. K2-3 is a bright (Ks = 8.6 mag) M dwarf star hosting three planets from 1.5 — 2 $R_\oplus$ at orbital periods between 10 and 45 days. These planets receive 1.5 — 10 times the flux incident on Earth; planet d orbits near the habitable zone (Crossfield et al. 2015). The K2-3 system is an ideal laboratory for transmission spectroscopy with *HST* and *JWST* (Greene et al. 2016) and planet d is already being observed in HST GO-14862 (PI Benneke). However, RV measurements will be essential to interpret these results. To that end, new RV data have been collected and I am currently analyzing these data to measure the planet masses, as described in more detail in the next section.

HD106315 is a bright (V = 8.97 mag) F5 dwarf star hosting two planets from 2 — 5 $R_\oplus$ at periods of 9.55 days and 21.06 days, respectively (Crossfield et al. 2017; Rodriguez et al. 2017). With HD106315, I will be probing the composition and system architecture of these planets. Due to the large transit depths and the high rotation velocity of HD106315, I will measure the orbital obliquity via Doppler tomography or the Rossiter-Mclaughlin (R-M) effect (Crossfield et al. 2017; Rodriguez et al. 2017). The estimated R-M effect will have an amplitude as much as 12.7 m/s, which should be detectable with APF and Keck. My proposal has already been awarded APF time to observe two transits in this system to measure the system's spin-orbit alignment. Measuring the orbital obliquity for Neptune-sized (or smaller) planets has rarely been accomplished; therefore, my results will serve as an excellent test-case for possible formation mechanisms of these planets. Bright host stars with small planet multiplicity make both K2-3 and HD 106315 ideal to determine masses using RV follow-up and to later constrain their atmospheric composition via transit spectroscopy with *HST* or *JWST*.

Current Progress:

Using data taken with Keck/HIRES, I have begun to constrain the masses of the three planets in the K2-3 system (Figure 1). I analyze the data using a Markov chain Monte Carlo approach, called RadVel, in order to find the best fit parameters. For now I assume that the planet orbits are circular. The period, time of inferior conjunction, and argument of periastron for each planet is determined from the *K2* transit data. The masses and jitter are allowed to vary. These mass measurements are the most precise to date and will continue to improve with more data on the system. Observations are ongoing and the final analysis will be published at the beginning of this fellowship.

With these masses, I have plotted the three K2-3 planets on a mass-radius plot in order to infer their compositions (Figure 2). Planet b is not a rocky planet and must have a substantial complement of volatile elements, showing that it remains an excellent *JWST* target. The same likely applies to planet c, though its uncertainties are greater. The composition of planet d remains unconstrained, hence our desire for more data.

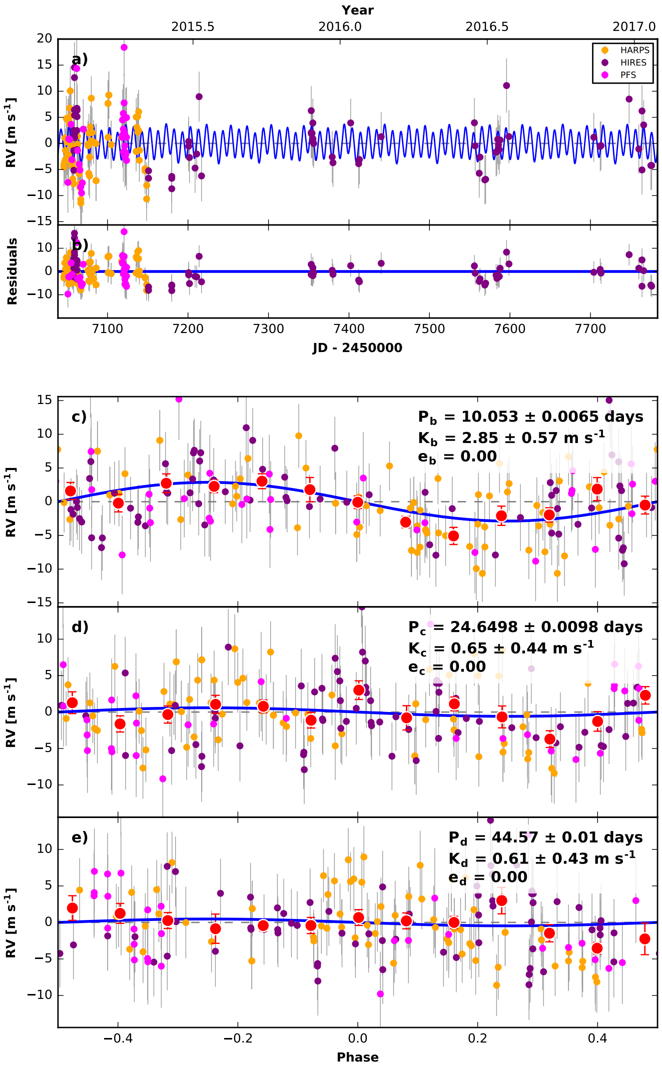

Figure 1: My RV analysis of the K2-3 system. Planet b's mass is measured with high confidence, and all three planets' properties are shown in Figure 2.

The APF collects RV measurements of many stars every night. I am working with Professor Vogt to analyze a few of these systems from *K2*, like HD106315 as described above. However, with hundreds of systems observed, I am unable to analyze each system myself. The larger-amplitude, easier-to-detect signals are well-suited for motivated undergraduate students. This semester, I am mentoring five undergraduate students in an Introduction to Research class lead by Professor Murray-Clay. This class is targeted at first year students who have declared a Physics major and are from typically underrepresented groups in Physics in order to increase the retention of these groups. Under my guidance, these students are extracting planet masses from APF data and calculating bulk densities in order to increase our sample size of planet density measurements and add to our ability to constrain planet composition and formation.

Three-Year Research Plan: I am leading the analysis of these *K2* systems which are archetypes for the brighter *TESS* targets that I will next characterize. During the first year of this fellowship, these systems will be my research priority. I plan to publish a paper on K2-3 at the beginning of the first year and one on HD106315 at the beginning of my second year. During my second year, TESS southern hemisphere observations will begin in mid 2018. I will choose follow-up targets from the northernmost targets, as they are accessible from APF & Keck. We will observe these accessible southern targets using Keck and APF in order to refine the analysis process and plan future observations.

During the second year I will travel to a AAS meeting to present my work on the *K2* targets. By the end of my second year, Northern hemisphere observations will begin mid-2019; the majority of these targets will be accessible from APF & Keck. *TESS* will discover ∼1000 sub-Neptune planets (Sullivan et al. 2015); I will be well prepared to identify ideal targets and observe these bright planets using APF and Keck (Figure 3). In the final year, KPF RVs will greatly increase our precision and observing speed. I will analyze the TESS sample to determine the masses and compositions of a number of sub-Neptune planets. These compositions can be used to test current formation methods of these close-in, small planets. Also, these mass measurements will be used to prepare for and understand atmospheric studies with HST and the James Web Space Telescope (JWST). Precise mass measurements are necessary to pick the best targets and to accurately interpret the atmospheric spectra as the mass affects the spectral signal. This work will culminate in a large synthesis paper on the composition transition between sub-Neptune and super-Earth planets that will form the capstone of my dissertation.

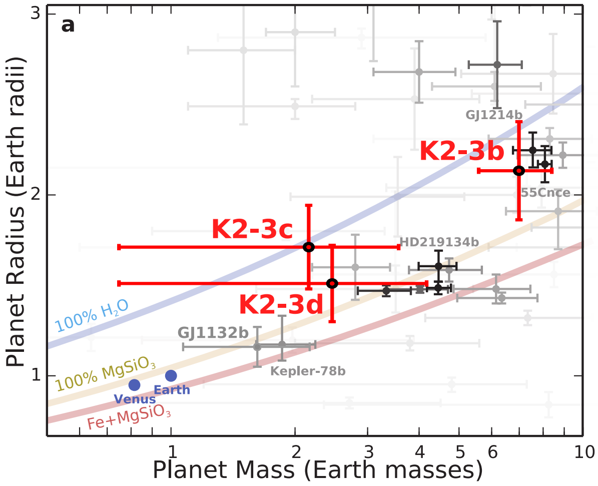

Figure 2: Three K2-3 planets (b,c,d) and their one sigma uncertainties in mass and radius (red) along with those of other exoplanets (grey). Also shown are theoretical mass-radius curves for various compositions. Planets with smaller fractional mass and radius uncertainties are darker. (Adapted from Berta-Thompson et al. 2015.)

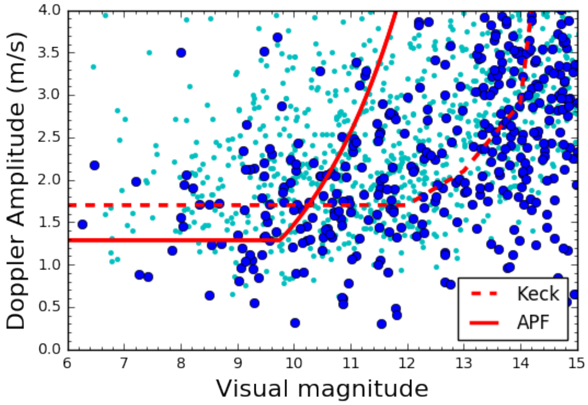

Figure 3: Simulated TESS planets (Sullivan et al. 2015) under 2 $R_\oplus$ (larger circles), 2 - 5 $R_\oplus$ (smaller points) and the sensitivity of APF (line) and Keck (dashes). I have access to both APF and Keck; dozens of small planets will be available for my proposed research.

Impact & Relevance to NASA Scientific Objectives: NASA's planetary science goals as stated in the Science Mission Directorate 2014 Science Plan include (1) *explore the origin and evolution of the galaxies, stars and planets that make up our universe* and (2) *discover and study planets around other stars, and explore whether they could harbor life.* My research supports three NASA missions, *K2*, *TESS*, and *JWST*. I will be analyzing planets found by *K2* and *TESS*, in order to characterize their masses and infer their compositions. This is directly applicable to goal (1) in that I will be exploring the types of planets that make up our universe. My program also directly supports the *TESS* missions top-level science requirement, to measure the masses of forty small exoplanets. Furthermore, my research program will determine planets that are suitable for followup with NASA's future *JWST* mission in order to characterize their atmospheres. Atmospheric characterization is directly applicable to goal (2), as chemical signatures of life could be detected in exoplanet atmospheres. *HST* is already observing K2-3, and a few other *K2* planets; *JWST* will provide more precise transmission spectroscopy measurements. There are currently very few good candidates for atmospheric characterization with *JWST*; therefore, discovering and characterizing exoplanets around nearby bright stars pre-*JWST* is crucial for the effective use of *JWST* resources.

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