Exoplanet Research Program
Abstracts of Selected Proposals
(NNH17ZDA001N-XRP)

Below are the abstracts of proposals selected for funding for the XRP program. Principal Investigator (PI) name, institution and proposal title are also included. 111 proposals were received in response to this opportunity. On October 12, 2017, 16 proposals were selected for funding.

Sean Andrews/Smithsonian Astrophysical Observatory
The Roles and Origins of Small-Scale Substructures in Protoplanetary Disks

The canonical model for the formation of terrestrial planets and giant planet cores implicitly relies on an early and very efficient phase of planetesimal growth in a gas-rich disk. But, as theorists have known for decades now, there are some formidable obstacles to meeting that requirement. Many of these problems, and potentially their solutions, are associated with the growth and migration of "pebbles" (mm/cm-sized solids) in the first few million years of a disk's lifetime. That is fortuitous, since the thermal continuum emission from these particles in nearby disks can be readily detected and resolved with radio interferometers. Observations offer several lines of evidence that qualitatively support theoretical models for the growth and migration of disk solids, but also demonstrate a quantitative tension with the efficiency of that evolution.

Recent observations have revealed prominent localized concentrations of that radio continuum emission on small (few AU) scales in a few disks. These striking substructures, manifested as arcs, spirals, and concentric rings and gaps in the spatial distributions of mm/cm-sized solids, are likely the hallmarks of a general solution to the tensions with the disk models. They signal that some mechanism shepherds solids into confined areas by slowing or halting (and perhaps attracting) their migration. Theoretical work has suggested that the conditions in such concentrations are favorable for triggering instabilities that can rapidly convert pebbles into much larger planetesimals. Various mechanisms to account for the observed substructures have been proposed, including local gas pressure maxima induced by dynamical effects, fluid instabilities, and abrupt variations in the properties of the disk material. Perhaps the most tantalizing hypothesis is that these disks have been dynamically sculpted by previous generations of planet formation.

These small-scale disk substructures appear to be fundamental pieces to the planet formation puzzle. We are proposing for support to (1) conduct the first high resolution survey of mm-wave continuum (and molecular line) emission from disk substructures; (2) systematically quantify their morphologies, amplitudes, scales, separations, symmetry, and dependence on host star properties; and (3) vet the theoretical mechanisms that have been proposed to produce them. These investigations will dramatically improve our understanding of protoplanetary disk structures and the origins of exoplanetary systems. They will also provide guidance for designing direct imaging search strategies and

interpreting the upcoming vast microlensing catalogs available for exoplanets with long orbital periods from current and future NASA facilities.

Timothy Brandt/University of California at Santa Barbara
Discovering and Characterizing Exoplanets with High-Contrast Spectroscopy

Though thousands of exoplanets have been discovered, only a few of the most massive, either at very close or very wide separations, are amenable to spectroscopic characterization. The rest are observed only through their effects on their host stars: their orbits, masses and/or radii are all that is known. By obtaining spectra of massive, wide-separation planets, we can probe their atmospheric chemistry and abundances, constrain their surface gravities (and hence their masses), and infer their heat supply at formation. Spectroscopic characterization can resolve the controversy over how these planets formed and enable us to understand the physical state of their atmospheres, including temperature and pressure profiles and the formation of clouds and hazes. The same techniques will ultimately provide a way to search for nonequilibrium chemistry in the atmospheres of rocky planets, a potential signature of life.

We propose to use the new instruments SCExAO and CHARIS on the Subaru Telescope to (1) conduct a survey for new exoplanets around nearby young stars visible from the northern hemisphere, (2) obtain, calibrate, and characterize spectra of known and newly-discovered planets, and (3) use these spectra to infer planet properties and connect them to theories of giant planet formation. CHARIS has the broadest simultaneous bandpass of any instrument in its class, which enables us to distinguish diffracted starlight from the light of faint exoplanets close to their stars. SCExAO's use of incoherent satellite spots (Jovanovic et al. 2015) will enable us to accurately calibrate the position and brightness of planets.

Spectra obtained with the aid of high-contrast imaging are, by their nature, difficult to calibrate and characterize. This makes proper statistical comparisons with theoretical spectra impossible, and makes it difficult to infer the planets' chemistry and atmospheric conditions. Published exoplanet spectra have used high-pass filters (Konopacky et al. 2013), generically omit covariances, and have used a range of extraction algorithms in an attempt to understand systematic uncertainties (Macintosh et al. 2015). Our research program will combine new extraction algorithms with SCExAO's calibration capabilities to enable deeper searches for new planets, and statistically rigorous comparisons of observed spectra with theoretical models. These comparisons are the only way to infer the exoplanets' chemical abundances, which could point to the locations in the protoplanetary disk where the planets formed. Our observed and calibrated spectra will provide much-needed tests of theoretical models of exoplanet and brown dwarf atmospheres, while the algorithms and statistical techniques we develop will be applicable to data from JWST and from future missions like WFIRST, HabEx and LUVOIR.

David Charbonneau/Harvard University

Discovery and Atmospheric Reconnaissance of the Most Spectroscopically Accessible Temperate Transiting Terrestrial Exoplanets

The Science Plan for NASA's Science Mission Directorate identifies the goal of discovering and studying planets around other stars, and exploring whether they could harbor life. Transiting systems provide a unique opportunity to do this, by allowing us to study the atmospheres and bulk compositions of exoplanets without the need to spatially resolve them from their parent star. While many successful studies have targeted Jupiter and Neptune sized planets orbiting solar type stars, the observational signal sizes rapidly become too small for Earth-sized planets orbiting these stars. For the near future, the only way to achieve the goal of characterizing an Earth-like planet is to use JWST and the upcoming ground-based ELTs for an extensive campaign to observe one transiting a bright, nearby, mid-to-late M-dwarf, where the small size and low luminosity of the stellar host boost the planetary signal size into the measurable range.

Since the Kepler and K2 missions cover only 6% of the sky, they are unlikely to discover the optimal planets for such work. The TESS Mission will target nearby stars, but owing to its small 0.1m apertures it is limited to ones that are bright at optical wavelengths: TESS will not survey mid-to-late M-dwarfs effectively. Moreover, with such a large national investment in JWST, it is essential that we invest in an insurance policy to ensure the identification of the most compelling JWST targets even if the TESS Mission is delayed, or fails entirely.

The MEarth Project consists of two telescopic arrays, one surveying the northern sky from Mt. Hopkins, Arizona, and the second surveying the southern sky from the Cerro Tololo Interamerican Observatory, Chile. Each consists of 8 x 40cm telescopes, designed to search for small planets around 3500 of the most nearby mid-to-late M-dwarfs over the whole sky. This survey discovered GJ1214b, which is by far the best studied mini-Neptune class exoplanet, and GJ1132b, which was the first terrestrial exoplanet that can be investigated spectroscopically. In April 2017, the MEarth team published the discovery of LHS1140b, a temperature transiting terrestrial planet that is arguably the first such world for which astronomers could undertake a search for atmospheric biosignature gases through the technique of transmission spectroscopy.

The goals of this proposal are threefold: First, the bulk of our effort will focus on the operation of the MEarth survey, and we aim to discover several more worlds akin to LHS1140b. Second, we will measure the masses of these planets via the Doppler technique and constrain their bulk densities. Third, we will undertake preliminary spectroscopic reconnaissance of their atmospheres with ground-based observatories, to determine how best to undertake a detailed spectroscopic scrutiny with JWST.

In searching the closest and smallest main-sequence stars for planets, we will also aid other ongoing and planned exoplanet surveys by determining the rotation periods, variability amplitudes and activity levels of these stars. Furthermore, we will measure high cadence and long duration light curves, which may be essential to correct for the effects of stellar

activity in radial velocities and spectroscopic studies of planetary atmospheres. The MEarth observatory will also assist with follow-up of planetary discoveries from the K2 Mission.

This proposal seeks support for the crucial 3 year period spanning the launch and commissioning of JWST. The MEarth data are released to the public annually.

Laird Close/University of Arizona
Discovery of Accreting Planets with the MagAO SDI+ High Contrast Imager on the 6.5m Magellan Telescope: Defining the JWST Protoplanet Sample

MOTIVATION TO DETECT PROTOPLANETS: Thousands of gas-rich exoplanets are known today. Yet, until recently, none of these were young forming/accreting "protoplanets". Multi wavelength observations (AO and JWST) of such protoplanets are the best approach to unraveling the mystery of planet formation.

TECHNICAL BACKGROUND OF THE MagAO INSTRUMENT: The PI and his team have built and commissioned an advanced adaptive optics (AO) system at the 6.5-m Magellan Clay telescope at Las Campanas Observatory, Chile. This system is called MagAO (PI Laird Close) and it uses an adaptive secondary mirror (ASM) with 585 actuators to apply the correction measured by its high-order pyramid wavefront sensor (PWFS) 1000 times each second. Because we can correct at wavelengths as short as H-alpha (656.3 nm), the MagAO system regularly produces the highest-spatial-resolution deep images to date. MagAO has been on-sky over 160 nights now and has been in regular science operations at Magellan for 3 years. MagAO is the only telescopic system (on the ground or space) that has published high spatial resolution <0.03 arcsec (<30 mas) images at the strongest hydrogen gas accretion emission line: H-alpha (Close et al. 2013). Just recently (Feb 2017) the team commissioned their "SDI+" optical device that enables very high-contrast, high-spatial resolution images (planet/star=10^-3 at 80 mas; 10^-4 at 100 mas) at H-alpha. With the (now outdated) SDI device this team made the first definite detection of accreting protoplanets at H-alpha in the gap of the LkCa 15 transitional disk (Sallum, Follette et al. Nov 19, 2015 issue of Nature). Their newly upgraded SDI+ optics enables a 300% improvement in contrast over SDI.

METHODS/TECHNIQUES: Transitional disks are disks around young stars that have dust-poor gaps. A common hypothesis is that multiple (2-3) massive accreting planets near the inner and outer edges of the wide gap are needed to keep it dust poor (Dodson-Robinson & Salyk 2011). The PI and his team will utilize MagAO's absolutely unique ability to take H-alpha (656nm), and continuum (642nm) images simultaneously with SDI+ to complete, and enhance, a survey, called GAPplanetS+, for protoplanets.
SURVEY#1 (GAPplanetS+): the 25 nearest (~150 pc), youngest (~1-3 Myr), brightest (R<12 mag) large gap (>130mas) transitional disks for the most sensitive survey of protoplanets in transitional disks.

SURVEY#2 (XRProtoplanetS+): 17 very close (~50-100pc), bright (I<10 mag), young (3-10 Myr) TTauri stars around non-transitional disks.

Science objectives of the proposed Surveys:

1. Discover low mass (0.5-13 Mjup), young, accreting extrasolar protoplanets,
2. Determine if core-accretion formation theory is correct and young planets do pass through a phase of rapid gas accretion and bright H-alpha flux (as already observed in LkCa 15b),
3. Characterize the spatial distribution, H-alpha luminosity, accretion rates, frequency, and ages of protoplanets at 4-10 AU and wider orbits,
4. Determine the influence of planets on transitional disk gaps,
5. Determine if older (~3-10 Myr) non-transitional disks also have detectable accreting planets.
6. Rapidly publish a public catalog of at least ~11-18 protoplanet/circumplanetary disk candidates as high-quality targets for JWST thermal follow-up. Hence this proposal is very relevant to the XRP/NASA science plan and goals.

PROOF-OF-CONCEPT: The LkCa 15b planet captured ~50% of the star's accretion flow, and was ~1,000x brighter at H-alpha than the predicted photospheric H band flux from the most optimistic planet formation models. Indeed the planet was not detected at H band -- but was easily detected at H-alpha 120x fainter than the star (at just 93 mas; 15 AU separation). Hence it is clear that searching for accreting planets at H-alpha inside the gaps of transitional disks is a very good strategy for detecting protoplanets, as the case of LkCa 15b proved.

Rebekah Dawson/Pennsylvania State University

Assessing the Hallmarks of Migration and In Situ Formation in Multi-Exoplanet Systems

Planetary migration can displace a planet from its birthplace to its present day location. Early discoveries of giant exoplanets orbiting close to their host stars (e.g., 51 Peg b) and in or near mean motion resonances (e.g., GJ 876 b/c) were interpreted as evidence for migration's critical role in the origins of planetary systems and inspired two decades of theoretical investigations of migration mechanisms. Migration has been invoked to explain more recent discoveries of systems of several planets in mean motion resonant chains (e.g., HR 8799; GJ 876 b/c/e; Kepler 223 & 80; TRAPPIST-1). However, recent observational and theoretical studies have called into question the prevalence of planet migration. Most multi-planet systems discovered by the Kepler Mission are not in or near orbital resonance, which would be expected from many models of planet migration. Meanwhile, simulations of planet formation have shown that planets with modest gas envelopes may be able to form close to their host stars. It is currently ambiguous what role, if any, migration plays in establishing exoplanet orbits and compositions. Here we aim to address whether migration plays a major role in establishing observed properties of multi-exoplanet systems.

We will first focus on mechanisms to establish mean motion resonant chains. Many studies have assumed that chains of planets in or near mean motion resonance (for example, in the TRAPPIST-1 system) are a smoking gun of large-scale migration. Other studies have proposed that resonant chains can be established with very modest migration or dissipation, such as eccentricity damping from the gas disk, but may require implausibly fine-tuned initial conditions. We will use simulations to systematically investigate how often systems are captured into resonance chains with dissipation alone, with migration over a small distance, and with large scale migration, and to assess how the outcomes depend on planet and disk properties.

Next we will address whether migration vs. in-situ formation creates observable differences in properties observed today, both for systems within and outside of resonant chains. We will investigate this question through two foci:

Small (sub-Neptune) planets: we will simulate the evolution of initial configurations of proto-planets in resonant chains vs. growth fully in-situ. We will assess differences orbital and compositional properties for and trends between orbital properties and properties of planets (e.g., mass, gas envelope) and/or their host stars (e.g., metallicity). We will then compare to the observed sample of planets, such as those observed by \kep and radial-velocity surveys, accounting for selection biases and observational uncertainties. We will provide predictions that can be tested with upcoming instruments like TESS and NEID.

Giant planets: we will use simulations to assess whether initial configurations of gas giants in resonant chains affect the final eccentricity distributions and correlations between orbital properties and stellar ages. We will compare to current observations and make predictions for future observations.

Relevance to the Exoplanet Research Program: This proposal supports the goal of improving our understanding of the origins of exoplanetary systems by investigating the role of planet migration and in-situ formation in the early evolution of planetary systems. The proposal will provide observable consequences of the migration and in-situ formation mechanisms and indicate observational tests that can be employed to test the validity of the models. The proposal will carry out comparisons with properties of known planets and make predictions for observed properties that will be detectable with new surveys and instruments within the next five years, including NASA's TESS and NEID surveys.

Gaspard Duchene/University of California, Berkeley

On the edge: Assessing the Diversity of Protoplanetary Disks From a Unique Perspective

Understanding the remarkable diversity of planetary systems revealed in particular by the Kepler mission is a central goal of modern astrophysics. To shed a new light on this fundamental question, the core objective of this project is to assess the true diversity of structural properties among protoplanetary disks. Specifically, we aim at evaluating the degree to which processes such as vertical settling, radial migration and dust-gas

decoupling, all believed to be key initial steps towards planet formation, are common in circumstellar disks, and to determine the role they play in disk evolution. To circumvent the highly ambiguous nature of spatially unresolved observations, a disk's structure must be probed through high-resolution imaging over a broad range of wavelengths, from visible scattered light images to radio wavelength thermal emission mapping. Disks that are fortuitously oriented so that we view them nearly edge-on provide a natural occulter to the glare of the central star, enabling studies that are daunting "if not outright impossible" for disks seen at lower inclinations. In particular, the disk's vertical structure is in full display in this case, and the presence of tenuous amounts of material at large distances from the central star is readily revealed thanks to the natural effect of line-of-sight integration.

Our project, which builds on the legacy of several Spitzer and Herschel surveys to identify candidate edge-on disks in the first place, combines high-resolution imaging with HST, adaptive optics and sub-millimeter interferometric observations with state-of-the-art radiative transfer modeling. With over three dozen edge-on disks around solar-type and low-mass stars already imaged with HST and/or ground-based adaptive optics as well as ongoing ALMA programs to map a large subset in both sub-millimeter dust continuum and molecular emission maps, we are in an ideal position to perform highly uniform modeling studies, enabling both object-to-object comparisons and a full characterization of the overall demographics of protoplanetary disks. This thorough panchromatic modeling will allow us to assess the intrinsic diversity of disk structure on a sound statistical basis and to draw comparisons with the statistical properties of planetary systems. In addition, we will make predictions for future high-resolution mid-infrared JWST observations that will bridge the gap that exists between existing capabilities by probing deeper into these disks.

Understanding the planet formation process through studies of protoplanetary disks, and explaining the diversity of planetary systems that emerge from it, is directly relevant to NASA's "Exoplanet Research Program." Furthermore, this project builds on observations with previous and ongoing space mission led by, or with strong contribution from, NASA and will help prepare the planning and interpretation of future observations of protoplanetary disks with JWST. Finally, by directly involving two UC Berkeley undergraduate students, this project will provide exciting opportunities for students to get engaged in research in a STEM field.

Debra Fischer/Yale University
Extreme RV Precision: Separating Stellar Jitter from Orbital Velocities

The search for Earth-like planets with the radial velocity method requires measurement precision of about 10 cm/s. This level of instrumental precision will be reached by next generation spectrographs that provide very high fidelity data. The two key remaining contributions to the error budget for extreme precision radial velocities are "stellar jitter" – photospheric velocity contributions (pmodes, granulation, spots, faculae, meridional flows) and telluric contamination of the spectra. The ability to model these obscuring

signals would change the trajectory of exoplanet science by enabling detections and mass measurements of low mass planets and to by providing bulk densities for thousands of transiting planets.

The key objectives of this proposal are the development of statistical analysis tools that will allow us to (1) separate photospheric Doppler shifts from Keplerian Doppler shifts in high-resolution spectra and (2) mitigate the impact of telluric contamination. The work necessarily begins with simulated data where we can test the reliability of our methods, but will then be extended to existing archival spectroscopic data from HARPS, CHIRON, and HIRES.

Our proposed work builds on a principal component analysis (PCA) framework that we have already developed. We propose to explore more sophisticated machine learning algorithms, including sparse and functional PCA, which are designed to make use of the wavelengths of the spectrum that are most variable due to stellar activity and telluric absorption. We are also developing hybrid statistical methods, including a Doppler-constrained PCA that provides input to a Gaussian Process framework and Markov chain Monte Carlo methods. Our preliminary tests of this new method on simulated solar data demonstrated the ability to recover a Keplerian Doppler shift with a period of 7 days and an amplitude of 0.25 m/s in the presence of 7 m/s of stellar jitter from a 1% spot with a 10-day rotation period. The same techniques can be applied to model time-variable telluric contamination. Our combined model for Keplerian Doppler shifts, stellar activity, and telluric absorption will provide a powerful framework for modeling spectroscopic time-series.

The statistical algorithms must be developed now to make existing instruments more productive and to aid in the design of next generation spectrometers. The mitigation of stellar jitter and telluric contamination in radial velocity data will enable the detection of low mass planets and for follow-up of exoplanet host stars identified by space-based transit missions (Kepler and the Transiting Exoplanet Survey Satellite). The proposed work directly supports NASA's XRP priorities.

Nader Haghighipour/University of Hawaii
Dynamical Evolution of Circumbinary Disks and Embedded Planets

Science Goals and Objectives: The success of the Kepler space telescope in detecting planets in circumbinary orbits strongly suggests that planet formation around binary stars is robust, and planets of a variety of sizes and orbital configurations may exist in such environments. Accurate modeling of Kepler data has indicated that the orbits of many of these planets is close to the boundary of stability, and that they reside between major resonances with their host binaries. A survey of the currently known circumbinary planets (CBPs) indicates that the orbits of many of these objects are slightly inclined and they precess with rates that place them out of transit for the majority of the time. The latter strongly suggests that numerous CBPs may exist in non-transiting, inclined orbits. These findings, and the fact that the currently known CBPs are Saturn- to Jupiter-mass, combined

with unsuccessful attempts in forming CBPs close to the orbital stability limit has lent strong support to the idea that these planets formed at large distances and migrated to their current locations. To explain the observational characteristics of these bodies, and in order to be able to quantify the detectability those in inclined orbits, we propose to carry out a detailed, GPU-based, 3D study of the migration and dynamical evolution of planets in circumbinary disks, taking into account the evolution of the disk as well as its interaction with planetary bodies. In brief, we propose to 1) study the evolution of circumbinary nebulae using 3D radiative disk models, 2) study planet migration in these disks for different orbital inclinations and masses of the planet, 3) study the proximity of CBPs to the binary stability limit and their capture between mean-motion resonances, and 4) assess the detectability of inclined CBPs through the eclipse timing variation method by determining the probability of their capture in stable orbits.

We have addressed some of these issues by developing a complete 2D planet-disk interaction model for circumbinary systems. However, recent detections of episodic transits in three CBPs, namely, Kepler 413b, Kepler 453b, and Kepler 1647b have indicated that in general, the orbits of planets and their host binaries are not co-planar. That means, any treatment of planet-disk interaction and planet migration in circumbinary systems has to be carried out in 3D. We plan to use the new code FARGO3D, developed by collaborator Masset, to extend our current models of planet-disk interaction in circumbinary systems to three dimensions.

Methodology: To properly carry out our proposed tasks, we start by implementing a proper treatment of radiation transport and radiative cooling in 3D circumbinary disk models. The evolution and dynamical behavior of these disks will be studied for different values of their parameters and those of the binary. We will study the dynamics of the disk near the central binary and place constraints on the extent of the inner hole and its eccentricity as a function of the disk and binary parameters. Once the disk models have been developed, we will simulate the migration of planets. We will study the connection between the disk and planets' parameters, and their role in establishing the final orbital architecture of the system. Emphasis will be placed on the masses of the circumbinary planets to investigate the observed occurrence rate of planets around their host binaries. We will identify regions of CBP stability around the host binary for inclined orbits and evaluate the amplitudes of ETVs induced on the binary by these bodies.

Relevance to the goals of XRP: Our proposed projects are in direct relevance to the goals of NASA XRP. They include computational modeling of different stages of the dynamical evolution of circumbinary disks and their embedded planets. The results of these models will directly contribute to our understanding of the origins of exoplanetary systems.

Stephen Kane/San Francisco State University

Completing the Puzzle of Exoplanet Host Stars: Stellar Characterization in Support of TESS

It is frequently stated that we understand exoplanets only as well as we understand the host star. Such a statement is particularly true for low-mass dwarf stars, whose physical properties often diverge from stellar models. There have been concerted efforts in recent years to obtain observational constraints on the stellar models for low-mass stars, especially for those monitored by the Kepler & K2 missions. A further challenge includes the confusion that can be caused by the stellar rotation period of low-mass stars since that can often coincide with the range of orbital periods of planets that may exist in the Habitable Zone (HZ) of those stars. The concise characterization of exoplanet host stars is particularly important in the era of the Transiting Exoplanet Survey Satellite (TESS), since the instrument will be surveying most of the bright stars ($V < 12$) in the sky for transiting exoplanets.

The Automatic Photoelectric Telescopes (APTs) operated by Tennessee State University (TSU) are a collection of telescopes located at Fairborn Observatory in Arizona. For example, the T11 is a 0.8m telescope equipped with a two-channel precision photometer that uses a dichroic filter and two EMI 9124QB bi-alkali photomultiplier tubes to separate and simultaneously measure the Str\"omgren b and y photometric passbands. These telescopes have acquired millimag photometry for hundreds of bright stars over the past several decades, including many of the known exoplanet host stars. The Kilodegree Extremely Little Telescope (KELT) installations consists of two robotic telescopes that are conducting a survey for transiting exoplanets around bright stars ($8 < V < 11$). KELT-North has been operating at Winer Observatory in southern Arizona since 2005, whilst KELT-South has been operating at the Sutherland astronomical observation station owned and operated by SAAO since 2009. In total, the KELT has currently acquired observations of 5.5 million stars over 65% of the sky. Because of the long lifetime of the APTs and the KELT instruments, many tens of thousands of photometric observations have been obtained and are being utilized to better understand the nearby individual planetary systems.

This project will examine the years of photometry from the APTs and KELT instruments for known exoplanet host stars, including K2 systems, and many of the stars in the TESS Input Catalog (TIC). The magnitude range of these facilities overlaps strongly with the expected magnitude range of TESS and also covers a substantial amount of the sky. We will extract stellar variability, rotation rates, and long-term magnetic activity cycles of these stars in order to characterize their fundamental properties. Additionally, we will acquire new observations in conjunction with TESS discoveries to combine the activity cycles with the planetary transit times. The project will contain a wealth of data to be exploited and contributed back into the astronomical community. The project also aims to train undergraduates and graduate students in fundamental skills that will carry them forward in their careers. These skills include developing critical analysis of science literature, experience in the acquisition and reduction of data, and advanced techniques in data analysis and scientific creativity. Students will have opportunities to publish results

in refereed journals and present at astronomical and interdisciplinary research conferences. These results will be communicated to the public through popular science magazines and public talks. The exoplanet context of this work makes this very attractive to the public interest and is of broad interest and benefit to society.

Kevin Luhman/Penn State University
Searching for Brown Dwarfs at Planetary Masses

We propose to perform a survey for brown dwarfs at planetary masses (<10 Jupiter masses) in the nearest and richest star-forming clusters and associations (<10 Myr, d=150-300 pc). Candidate brown dwarfs will be identified through photometry and proper motions measured with wide-field imaging surveys (UKIDSS, Pan-STARRS1), archival images from the Spitzer Space Telescope, new images from the James Webb Space Telescope (JWST), and new and archival images from ground-based telescopes. These candidates will be observed with near-infrared spectroscopy to confirm their youth (and hence cluster membership) and cool nature. Through this survey, we seek to obtain samples of young planetary-mass brown dwarfs that are as large as possible (>50) and that reach the lowest possible masses (~1 Jupiter mass). These objects can then be used to improve our understanding of the formation of planets in the following ways:

1) The lowest mass at which free-floating brown dwarfs are able to form provides a constraint on the possible formation mechanisms for planetary-mass companions. If free-floating brown dwarfs form down to a given mass (e.g., 1 Jupiter mass), then it is plausible that some companions at similar masses have formed like binary stars (e.g., cloud core fragmentation).

2) It has been previously proposed that mid-infrared spectra may contain signatures that indicate whether a substellar object has formed via core accretion within a circumstellar disk (i.e., a planet) or through the collapse of a molecular cloud core (i.e., a brown dwarf). Future studies can verify the presence of such signatures through the comparison of spectra (especially from JWST) of free-floating brown dwarfs found in our survey and planetary companions from direct imaging surveys.

3) Future studies can use JWST to obtain mid-infrared photometry for the planetary-mass brown dwarfs found through this proposal, which can determine if they harbor circumstellar disks. In this way, those studies can identify the lowest mass at which brown dwarfs have the raw materials for making planets (i.e., what are the smallest “stars” that could potentially harbor planets?).

Renu Malhotra/University of Arizona

Distribution of Planet Masses, Planet-Planet Separations and Dynamical Lifetimes of Planetary Systems

The objectives of this research are to improve our understanding of the dynamical architectures of planetary systems and the overall mass distribution of planets in the Galaxy by using available exoplanet observational data sets in concert with theory and modeling of their orbital dynamics. Observational data sets of exoplanets are expanding rapidly (thanks to NASA missions such as Kepler and the forthcoming JWST, TESS, and WFIRST), but their theoretical interpretation has significantly lagged. Exoplanet detection and confirmation pipelines now routinely check whether the planetary systems they discover are likely to be dynamically stable. At the same time it is increasingly recognized that observed planetary architectures are often quite close to the "edge of dynamical stability".

In the first project, we will apply the tools of N-body numerical simulations to observed close-in multi-planet systems discovered by Kepler to assess their distribution of dynamical instability lifetimes. We will identify the common signs of imminent instability as well as common signs of longevity for planetary systems on the edge of dynamical stability. This project will produce predictions of the distribution of stable planetary architectures testable by future large samples of multi-planet systems such as those observed by the forthcoming TESS survey.

In the second project, we will continue with numerical simulations of unstable systems to assess post-instability planetary architectures. It has been suggested that multi-planet systems with fewer, more widely spaced planets could be the result of collisions between planets in originally more tightly packed systems. By modeling two different scenarios of collision outcomes (that collisions are either destructive or mostly accretional), we will generate simulated distributions of post-instability planetary systems arising from a variety of pre-instability planetary architectures; comparison with the observed Kepler planetary systems will test the idea that a fraction of the observed systems underwent past instabilities. This project will also provide predictions for the frequency of planet-planet collisions around dwarf stars as a function of system age, to be compared with the observed frequency of infrared-excesses around dwarf stars.

In the third project, we will consider anew the relationship between orbital separations and planetary masses in marginally stable multiple planet systems and derive an improved estimate of the planet mass distribution function. While various previous studies have taken a deterministic approach to compute dynamical lifetimes as a function of the dimensionless "dynamical separation" (orbital spacing in units of the mutual Hill radius of two adjacent planets), we propose a statistical approach, using the results of our first two projects to characterize the distribution of dynamical separations as a function of dynamical lifetimes in diverse planetary systems. With these results in hand, we will leverage the Kepler dataset of well determined orbital periods in hundreds of multiple planet systems to predict the overall mass distribution function of close-in planets. Our predicted mass

distribution function will be observationally testable by both the forthcoming TESS transiting planet sample and by the future WFIRST miscrolensing planet sample.

Our proposed investigations are relevant to XRP because they incorporate theory and modeling to facilitate interpretation of observational data from NASA's Kepler space mission, and they will make testable predictions for forthcoming exoplanet surveys as well as surveys of infrared excesses associated with planet-planet collisions. Our proposed studies will improve understanding of the origins of observed exoplanetary systems by characterizing their orbital dynamics.

Greg Rieker/University of Colorado-Boulder
Broadband, High-Resolution Frequency Comb Spectroscopy and Multi-Spectral Analysis of Water Vapor and Methane Absorption Up To 1300K For Improved Modeling of Exoplanet Atmospheres

The growing census of exoplanets includes a burgeoning amount of spectral data that can be useful for the characterization of exoplanetary atmospheres. Currently, atmospheres that resemble our solar system's terrestrial planets are well characterized by radiative transfer models that are founded on laboratory-based molecular spectroscopy measurements. However, for more extreme-temperature atmospheres, there is limited laboratory data available to create and validate models. In lieu of laboratory data, theoretical methods (e.g. EXOMOL) have produced data suitable for many aspects of exoplanet analyses. We contend that these theoretical methods are not yet proficient for extraction of scientific information for high-temperature, nonlinear polyatomic molecules (e.g. methane and water). The proposed effort utilizes a new resource for high temperature laboratory spectroscopy "a broadband, high-resolution dual frequency comb spectrometer coupled with a high-temperature optical cell facility" to make first-of-kind accurate laboratory measurements of the absorption spectra of water and methane at temperatures up to 1300 K. The measured data is then analyzed using a parameterized physical model (Labfit) that is already used for high fidelity spectral analyses for NASA missions. The resulting information is useful for both (1) direct spectral and radiative transfer modeling of exoplanet atmospheres; and (2) evaluation of the theoretical EXOMOL data. To that end, the proposed effort includes generating new spectroscopic databases for water vapor and methane in spectral regions important to current Hubble Telescope and future James Webb Space Telescope exoplanet observations. We will incorporate the databases into the EXCALIBUR science data pipeline, and assess the impact of the database improvements on retrievals from 57 current and planned observations.

Hilke Schlichting/University of California, Los Angeles
Giant impacts: The formation and diversity of super-Earths

Scientific Motivation and Goals

Super-Earths display a large diversity in their gas-mass fractions and bulk densities. This diversity is especially surprising for observed exoplanets residing in tightly-packed multiple-planet systems. These observations are challenging to explain by gas accretion and subsequent sculpting by photo-evaporation alone. We propose to investigate if the large observed range in exoplanet bulk densities may be due to one or two giant impacts that occurred late in the dynamical evolution of super-Earth systems once the gas disk dissipated. Such late giant impacts are likely to be common because super-Earths that contain several percent of their total mass in hydrogen and helium must have formed in the presence of the gas disk and their dynamical interaction with the disk is expected to have resulted in migration and efficient eccentricity damping. This leads to densely-packed planetary systems. As the gas disk dissipates, mutual gravitational excitations between the planets cause their eccentricity to grow culminating in one or two giant impacts before reaching long-term orbital stability. In our past work we have shown that a giant impact can easily reduce the envelope-to-core-mass fraction of an exoplanet by factors of 2 or more leading to changes in bulk densities of factors of 2-4 (Inamdar & Schlichting 2016). However this past work has focused on the "mechanical" aspect of the impact only and consisted of following the shock generated at the impact site as it propagates through the planet and its atmosphere. Here we propose to complement this past work by examining the "thermal" aspect of the impact, by calculating the heating of the planet's core due to the impact and the resulting heat exchange between the core and the envelope. We plan to follow the thermal evolution of the planet and its envelope in time. We will parameterize the impact properties needed for complete atmospheric loss and those for partial envelope loss. We will test how the atmospheric loss depends on the atmospheric composition, the total atmospheric mass and the location from the host star. Preliminary results suggest that the "thermal" aspect of the impact may dominate the atmospheric mass loss for hydrogen and helium atmospheres. We will combine the "thermal" mass loss results with the atmospheric mass loss results that we obtained for the "mechanical/shock" component of the problem (Inamdar & Schlichting 2016) to determined the total envelope loss in exoplanet collisions. We will then use these results to test if the observed diversity of super-Earths bulk compositions can be explained by atmospheric mass loss due to giant impacts or if it has to be attributed to different formation paths of these systems.

Relevance to E.3 Exoplanets Research Program

The proposed work directly addresses the stated Exoplanets Research program goals to "understand the chemical and physical processes of exoplanets (including the state and evolution of their surfaces, interiors, and atmospheres)" and to "improve understanding of the origins of exoplanetary systems".

Sang-Heon Shim/Arizona State University

Breaking the Barrier Between Ice and Rock – New Mass-Radius Relations for Gas Giant, Icy Giant, Mini-Neptune, and Water World Exoplanets

The mass-radius relation has played a central role in understanding the compositions of the extrasolar planets from astrophysical measurements where it has been assumed that "gas", "ice", "rock", and "metal" do not react with each other significantly and that they therefore form separate layers in the interiors of the exoplanets. Specifically, some large exoplanets with slightly lower density than super-Earth have been modeled as water worlds where the rocky mantle is overlain by a few hundreds to thousands of kilometers thickness of ice. For icy and gas giant exoplanets, a mechanical mixture of ice and rock has been used to model the core. Although the equations of state of rock, metal, ice, and gas have been extensively studied individually, their mutual interactions at pressuretemperature conditions of the interiors of large exoplanets represent a new and completely unexplored planetary paradigm.

Our recent experiments have shown that pressure allows more water to be incorporated into the crystal structure of silica. Extrapolation of this trend predicts that ice and silica may even form solid solutions above 100 GPa. Because of their hitherto unknown thermoelastic properties, the existence of stable rock-ice "alloys" would have a profound impact on the interpretation of exoplanetary mass-radius relations based on the conventional notion of distinct "gas", "ice", "rock", and "metal" components.

We will undertake a systematic study of potentially new classes of materials formed from ice-rock reactions in the deep interiors of exoplanets by combining experiments and theoretical simulations. The overarching goal is to identify the pressure-temperature conditions where the traditional "rock" and "ice" barrier breaks down and a new class of materials forms in the Si-O-H system and, ultimately, provide updated mass-radius relations for exoplanet research.

Density functional theory will be used to develop a plausible range of crystalline models of silica-ice solid solution phases and predict their equations of state. The pressure-temperature stability fields of each candidate phase assessed by comparing its free energy to that of a corresponding silica+ice mixture. The most favorable candidate phases identified in this initial step will then inform high pressure experiments. In experiments, we will systematically explore the reactions between silica and ice at in situ high pressure and high temperature in the laser-heated diamond-anvil cell. Raman and infrared spectroscopy will be conducted for the samples at ASU in order to map the stability fields of new phases in the Si-O-H system. In situ synchrotron X-ray diffraction at high temperatures and pressures allows us to directly obtain structural information and the equations of state of the new phases. The combined experimental and computational results will then be used to construct new mass-radius relations for the exoplanet data analysis.

The proposed research will combine, for the first time, targeted laboratory and first principles simulations efforts to explore new chemistry in the Si-O-H system whose components have been traditionally considered incompatible with one another. As

suggested in our preliminary study, if the barrier between rock and ice breaks down in the interiors of large exoplanets, it will have profound implications for the interpretations of exoplanetary compositions from the mass-radius relation. The expected main outcome of this research project is improved mass-radius relations, which are expected to affect interpretation of a wide range of exoplanets, including gas giants, icy giants, mini-Neptunes, and water world exoplanets. Therefore, our proposed research will have immediate impacts for the ongoing and near future observations using ground-based telescopes and space telescopes (such as, CHEOPS, TESS, and Gaia) which will dramatically improve the precision of measured radii and masses of the exoplanets.

Keivan Stassun/Vanderbilt University

A Value-Added, Science-Enabling Catalog of Precise Stellar Properties for the TESS Mission

The upcoming NASA TESS mission has as its primary science goal the discovery of Earth-like planets whose properties (including especially their masses) can be measured. Just as the Kepler mission provided a Kepler Input Catalog (KIC), the TESS mission includes plans to create a TESS Input Catalog (TIC) that provides certain basic information about the potential target stars within the TESS field of view. However, there are a number of additional properties of the target stars that, while not required for the mission, would enable maximum science output from TESS with respect to discovery and characterization of transiting planets. One example is accurate and empirical stellar radius determinations from which to infer the most accurate planet radii; another example is stellar activity measures with which to select the systems most amenable to radial-velocity followup.

Our team has been developing techniques---including use of the Gaia DR2 parallaxes, whose delivery is expected during the first half of 2018---to determine a comprehensive suite of precise properties for the stars that will be targeted by TESS. The goal of this project is to develop a Community Value-Added TIC (CVA-TIC) of precise stellar properties for a large fraction of potential TESS targets, thus providing a science-enabling resource to the broader TESS community complementing and extending that provided by the mission.

Stellar properties that we expect to be able to provide include: a variety of stellar effective temperature estimates and new, empirically determined stellar radii and masses for 100 million stars; temperatures and radii and mass estimates for a carefully vetted sample of 1 million bona fide M-dwarfs; rotation periods and other activity indicators from long-term monitoring surveys such as our own KELT survey for 4 million stars; and the compilation of numerous large photometric and spectroscopic surveys, such as SDSS, UCAC4, APOGEE, and RAVE. Finally we provide 15 optical to near IR bandpasses and proper motions for more than 400 million objects.

This new resource -- the CVA-TIC -- will complement, enhance, and extend the TIC, and will be made available to the community for ready use via our Filtergraph data-visualization portal system as well as via the MAST server.

Neal Turner/Jet Propulsion Laboratory
Signatures of Planets Embedded in Wind-Driving Protostellar Disks

While modelers do a fair job of explaining exoplanets after they are found, there is little prospect of real predictive power regarding the planets not yet accessible to observations. The reason is that planetary systems' birth involves a sequence of poorly-known and intertwined processes, from sub-micron interstellar grains sticking together in protostellar disks, to turbulence and outflows that extract the disks' orbital angular momentum and stir the planet-forming ingredients, to the disk-planet torques that likely govern the systems' diverse architectures. We can bridge over several of these uncertain steps by finding planets still surrounded by the material from which they formed or are forming. Pinpointing when and where planets occur will tell us both starting points for subsequent orbital evolution, and ending points for the earlier stages of the planets' assembly. Discovering signs of embedded planets will enable multiple breakthroughs of the kind we need to advance our understanding of the origins of the thousands of known planetary systems, and gain insight into the still unknown parts of the planet population.

We propose to enable the detection of disk-embedded planets by producing quantitative predictions of their characteristic spectral signatures, using the best available knowledge of the planets' direct impacts on their surroundings. We will identify those signatures observable with current and near-future facilities, which let us spectrally resolve the orbital motion of gas in the planet-forming zone within a few AU, but not generally spatially resolve the features the planet raises in the disk. Specifically, we will produce synthetic spectroscopic and spectroastrometric time series spanning the planet's orbital period, to learn what signs we'll see if (1) hot Jupiters are near their final positions before the planet-forming gas and dust are cleared away, (2) gas giants lie near the snow line, and (3) a Neptune-mass planet, with enough mass to open a tidal gap in the surrounding solids, but too little to open a significant gap in the gas, disturbs the temperature and composition of the nearby disk material.

Our predictions will come from modeling the gas and dust magnetohydrodynamics, molecular chemistry, and continuum and non-LTE line radiative transfer of disks with and without planets. The models will treat in detail the disk atmosphere and wind, their photodissociation and ionization by the young star's ultraviolet and X-ray emission, the torques they apply to drive the disk's overall accretion flow, and their molecular emission. Along with planet signatures such as disturbances in the stellar illumination pattern and shocks and rarefactions in the disk and wind, with their impacts on the temperature and composition, we will investigate turbulent fluctuations as a potential confounding factor, seeking ways to distinguish these from the true planet signatures. This approach will make it possible to use the compositional and kinematic information that spectroscopy and spectroastrometry provide, and overcome the ambiguities plaguing attempts to interpret continuum features, such as dark rings, as cleared by embedded planets.

The results of the effort will guide searches for the signatures with spectrographs on ground-based infrared telescopes and the James Webb Space Telescope. The results also will inform our contributions and those of the community to the development of future facilities to find and characterize exoplanets, including LUVOIR, HabEx and the Origins Space Telescope, three of the four flagship space observatories NASA has tasked astronomers with studying for the 2020 Decadal Survey. Thus the proposed work directly supports the Exoplanets Research Program goal of understanding exoplanetary systems, both by improving knowledge of their origins and by supporting efforts to provide high-value exoplanet targets for current and future NASA observatories.