Exoplanet Research Program
Abstracts of Selected Proposals
(NNH18ZDA001N-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. 117 proposals were received in response to this opportunity. On October 19, 2018, 16 proposals were selected for funding.

Ellyn Baines/Naval Research Laboratory
Characterizing TESS Target Stars Using Optical Interferometry

The Transiting Exoplanet Survey Satellite (TESS) is on its way to begin its ground breaking work to discover transiting Earth-like planets around nearby, bright stars. There is no doubt TESS will produce remarkable science, but because the transit method provides the ratio between the star's and planet's sizes, our knowledge of the planets will be limited by how well we know the host stars.

We propose to use the Navy Precision Optical Interferometer (NPOI) to directly measure the angular diameters of TESS targets. The NPOI is capable of reliably measuring stars with angular diameter errors of 2$\%$ or lower. With such precision, we will be able to determine each star's effective temperatures and physical sizes precisely as well.

Not only will we bring the error down significantly on the stars' and therefore planets' sizes and densities over indirect methods that estimate stellar radii, we will also use the measurements to place each star on an H-R diagram in order to determine its mass and age. Every time we are able to better characterize the star, we take a big step forward in how well we can characterize the planet, too.

Our final product will be model-independent sizes for 10-15 TESS targets per year of the three-year program. We will focus on newly discovered exoplanet hosts as the data are released. For stars without known planets, these measurements will lead to an enhanced knowledge of our neighbors. For stars that do end up having planets, these improved stellar parameters will lead to planetary parameters with higher precision, primarily their sizes and densities.

This work is responsive to the XRP program goal to "observationally characterize exoplanets, their atmospheres, or specific host star properties that directly impact our understanding of the exoplanetary system, in order to support NASA's ongoing exoplanet surveys." We are also relevant to NASA's strategic goals in space science to "discover and study planets around other stars" as well as "explore the origin and evolution of the galaxies, stars, and planets that make up our universe."

Jonathan Fortney/University of California, Santa Cruz
A Comprehensive View of Giant Planet Atmospheres in the JWST Era

Proposal Summary Objectives:
We aim to understand the atmospheric spectra, structure, and composition of the atmospheres of giant exoplanets in the era of the James Webb Space Telescope. JWST will provide rich diagnostics on the atmospheres of a wide range of transiting and directly imaged planets, in particularly in thermal emission for both kinds of objects, and in transmission for transiting planets. We expect that for hydrogen-dominated atmospheres, from sub-Neptunes to Super-Jupiters, over the next 3 years to see significant gains in our knowledge. The field will move from our current provisional understanding to finally being placed on secure footing with significantly observational and theoretical work. This proposal is focused on the essential modeling and theoretical work that is needed to make these potential gains a reality.

Methodology:
Our group has long pioneered the use of 1D radiative-convective models within the “self-consistent” framework. Within these models we can explore the role of convection, including modifications to adiabatic structure, cloud opacity within the framework of a physically motivated cloud model, stellar irradiation across a range of host star types, and a variety of chemical abundances. We aim to significantly upgrade a number of aspects of our modeling tools, including our tabulation of atmospheric opacities, our treatment of non-equilibrium chemistry due to vertical mixing, and the radiative transfer solver we use for incident fluxes. Furthermore, this work will be paired with inverse models (“atmospheric retrieval") where appropriate, in tandem with self-consistent models, to yield the largest gains in our understanding of these atmospheres. Additional work will focus on the use of machine learning algorithms to understand what JWST observational setups will bring the greatest gains in atmospheric knowledge.

Relevance:
The proposed modeling investigations seek to advance our knowledge and understanding of the atmospheric composition and structure of exoplanets. The work is well suited to the NASA Exoplanets Research Program, whose "broad objectives include the determination of composition, dynamics, energetics, chemical behaviors of extrasolar planets..."

Murthy Gudipati/Jet Propulsion Laboratory / California Institute of Technology
Laboratory Simulation of Organic Aerosols in Exoplanet Atmospheres

Scientific Objectives: With increasing detection of exoplanets and spectroscopic characterization of exoplanet atmospheres, our knowledge base of other stellar systems and planets around these stars is expanding significantly. However, there have been severe limitations on the analysis of observational spectroscopic data and on the understanding of the physics and chemistry, particularly in hot-Jupiter atmospheres due to the lack of relevant laboratory data. Further, some recent observations suggest that

aerosols are present in several exoplanet atmospheres but their nature and formation mechanism between condensate clouds and photochemical hazes remain largely uncertain. The role of aerosols is becoming critical in understanding exoplanet atmospheres and laboratory investigation of aerosol formation and properties is crucial for their characterization and the interpretation of actual and future observations.
In order to fill this gap, we propose to conduct laboratory photochemistry studies by subjecting relevant gases (H2, CO, CO2, N2, CH4, etc.) to ultraviolet (UV) light at various temperatures (300 – 1800 K). The goals of this high temperature radiation-induced photochemistry of gas-phase molecular mixtures are: 1) To determine the aerosol formation efficiencies in exoplanets whose observable atmospheric temperatures vary between 300 K and 1800 K, a range that covers relatively cool terrestrial exoplanets to hot-Jupiter-like exoplanets. 2) To analyze the chemical composition and measure the optical properties from the ultraviolet to the infrared of the aerosols under the range of conditions reflecting the likely atmospheric temperatures of the most interesting transiting planets known today and those that are likely to be found in the future by TESS and spectroscopically characterized by JWST.

Methodology: We will be leveraging on the investment made by JPL in building the "Cell for Atmospheric and Aerosol Photochemistry Simulations of Exoplanets" or CAAPSE, which enables photochemistry and spectroscopy in the UV-Vis to IR wavelengths (120 nm – 7 microns), using FTIR and UV-Vis instruments. We will undertake laboratory simulations at high-temperature and low-pressure (a few mbar to 10s of mbar). We will investigate the effect of the temperature and the gas composition on the production efficiency and the properties of the aerosols. We will analyze the composition of the end-product non-volatile aerosols with IR spectroscopy (1 to 20 μm) as well as our newly developed 2-Step Laser Ablation and Ionization Mass Spectrometry (2S-LAIMS). We will measure the optical indices of these aerosol analogs in the UV-Vis (200-1000 nm) by ellipsometry.

Relevance to the program: The proposed work addresses the XRP program element under â€œlaboratory studies'specifically addressing the following elements as outlined in the call: "understand the chemical and physical processes of exoplanets (including the state and evolution of their surfaces, interiors, and atmospheres)". The results of this research will benefit analysis and interpretation of a vast amount of existing spectral data from exoplanets as well as data from future missions like the JWST. This research will also improve our understanding of the physics and chemistry occurring in exoplanet atmospheres.

List of Funded Team Members: Dr. Murthy S. Gudipati; Dr. Benjamin Fleury; Dr. Bryana L. Henderson; Dr. Mark Swain.

Renyu Hu/California Institute of Technology/JPL
Thermal Structure, Chemistry, and Observational Signatures of Cold Exoplanet Atmospheres

We propose to develop the basic theories and models of the atmospheric thermal structure and composition of cold exoplanets, i.e., the exoplanets that have conditions for water to condense in their atmospheres. Kepler, K2, and ground-based transit surveys have found ~80 cold exoplanets in transiting orbits. Among these planets, one Jupiter-sized planet and 8 smaller planets already have HST observations at 1 – 2 microns. JWST will be capable of providing a more detailed look into the atmospheres of these cold planets, as well as other cold planets soon to be discovered by TESS. To interpret the current observations and develop science cases for JWST observations will require a first-principle approach.

Building upon existing models, we will develop a 1D numerical model to simulate the atmospheres of cold exoplanets that may or may not be H2-rich. Such a tool is not currently available. Highlights of our approach include (1) a radiative-convective method that allows condensation of a major constituent in the atmosphere, (2) a self-consistent determination of a potential ocean-atmosphere interface, in presence of other soluble and insoluble species, (3) a treatment of condensation and dissolution of atmospheric NH3/H2SO4 and H2O in the exoplanet context, and (4) coupling between the atmospheric models and a state-of-the-art JWST simulation tools. With the models we will (1) determine the possible ocean-atmosphere interface of cold, water-rich exoplanets as a function of stellar irradiation, water abundance, and internal heat flux; (2) simulate a range of atmospheric transit spectra for the cold giant planet Kepler-16 b, PH2 b (Kepler-86 b), and Kepler-167 e and the cold and small planets K2-18 b, K2-3 d, LHS 1140 b, and TRAPPIST-1 d-h and to interpret the current observations; (3) determine the optimal wavelength ranges and observation modes with JWST to characterize the cloud pressure, ammonia dissolution in cloud droplets, and formation of sulfuric acid clouds on cold exoplanets.

This investigation is directly relevant to the Exoplanet Research Program because our proposed tasks will address a key objective in the NASA NRA: understand the chemical and physical processes of exoplanets. The proposed research will quantify key chemical and cloud-formation products in cold exoplanet atmospheres of a wide range of redox states and will establish spectral diagnostics of atmospheric composition for exoplanets in which water clouds can exist. Our modeling efforts will significantly facilitate the interpretation of current Hubble observations and will provide clear science cases for observations of a few cold exoplanets with JWST. The proposed research will also lead to realistic models of the reflected light spectra of small exoplanets at wide orbital separations, essential for evaluating future mission options including HabEx and LUVOIR.

Nathan Kaib/University of Oklahoma
Planetary Systems as the Bottom Levels of Hierarchies

Roughly 50% of Sun-like stars belong to multi-star systems, and the nearest exoplanet to Earth resides in the extended triple star system of Alpha and Proxima Centauri. Thus, understanding the dynamical histories of planets belonging multi-star systems is critical to interpreting exoplanet observations. Such systems cannot be modeled in isolation, for their stellar dynamics (and by extension planetary dynamics) are strongly influenced by external perturbations from the Milky Way. These perturbations often excite the stellar companions' orbits until they destabilize planetary systems. Yet, dynamical modeling of planetary systems in their larger environments is challenging because a complex larger-scale potential must be properly handled in concert with the efficient, accurate integration of near-Keplerian motion over much smaller scales. We have recently extended the planetary simulation code MERCURY to do just this, giving us unprecedented opportunities to study how planetary systems are influenced by their larger environments. Using this new tool, we will 1) reassess the dynamical history of Alpha Centauri and its potential planets, 2) understand how destabilized planetary systems differ from unaltered ones within Alpha Centauri, and 3) determine whether stellar birth clusters drive binary stars into disrupting one another's planetary systems. This work is highly aligned with the stated goals of NASA Exoplanet Research Program, as each of our proposed tasks promises to “improve understanding of the origins of exoplanetary systems,” and our work promises to significantly impact the field of exoplanets over the next 5 years.

Joel Kastner/Rochester Institute of Technology
Exploring Planet Formation in the Nearest Known Protoplanetary Disks

Science goals and objectives: Models of planet-forming disks indicate that processes such as dust grain orbital migration and segregation, the formation of grain ice mantles, irradiation-induced evolution of gas-phase molecular abundances, and disk gas dispersal together likely regulate the rate of planetesimal buildup and the eventual compositions of bodies ranging from comets to giant planet envelopes. Key aspects of such model predictions can now be tested directly, via suites of multiwavelength, subarcsecond resolution observations obtained with the latest generation of ground-based facilities. Further groundbreaking discoveries in the study of newborn exoplanets and their birthplaces are most likely to emerge from studies of those young (age < 30 Myr) stars that are nearest Earth. We seek to advance our understanding of the origins of exoplanets by continuing our program of multiwavelength observations and associated modeling targeting the rare examples of young stars within ~100 pc that are orbited by, and are actively accreting from, gas-rich protoplanetary disks.

Methodology: The program we propose to continue under renewed NASA Exoplanets support consists of submm/mm-wave imaging and spectroscopy to establish the residual masses, structures, and chemistries of the large-grain and gaseous components of nearby, molecule-rich disks within their outer, proto-Kuiper-Belt zones; X-ray and optical/near-infrared spectroscopy targeting the central stars and star-disk interaction regions;

optical/near-IR adaptive optics coronagraphic/polarimetric imaging to elucidate the dust density structures of the nearest known protoplanetary disks within their giant-planet-forming regions, with resolution on scales of a few AU; and modeling of dust and gas disk structure and chemistry that is informed and constrained by the foregoing observational campaign. Our team has already compiled a successful track record that spans all of these program elements.

Significance: In characterizing the physical conditions within gas-rich protoplanetary disks orbiting young stars in our "back yard", this proposed extension of our XRP program will further inform and constrain theories describing the processes governing giant planet and Kuiper Belt formation. We will also be able to better assess the likely signposts of recently formed (age <30 Myr) planetary systems and, hence, increase the likelihood of detection of such a "newborn" solar system. This research will contribute to our understanding of the origin of our solar system and of the breathtaking diversity of exoplanet systems. Thus, the proposed program is very well suited to the goals and objectives of the NASA Exoplanets Research program.

Dong Lai/Cornell University
Tides, Spins and Formation of Close-in Gas Giants

This proposal is devoted to a series of theoretical and computational studies on the formation of close-in giant planets, such as hot Jupiters (HJs, with periods < 10 days) and warm Jupiters (WJs, with periods 10-200 days). More than two decades after the discovery of the first HJs, the origin of HJs remains an outstanding unsolved problem in exoplanetary science. Many of these systems exhibit intriguing spin-orbit misalignments, i.e., the planet's orbital angular momentum axis is misaligned with the spin axis of the host star.

A large class of models for HJ/WJ formation rely on high-eccentricity migration, in which a gas giant (formed at a few AU) is pumped into a very eccentric orbit as a result of gravitational interactions with other planets or with a distant stellar companion, followed by tidal dissipation which circularizes the planet's orbit. While these models are successful in explaining some observations, several fundamental problems remain and concrete predictions are lacking in many cases. A major concern is the tidal dissipation in the planet. We have recently "discovered" that under some realistic conditions, tidal excitations of internal oscillation modes in the planet in an eccentric orbit can drive chaotic mode growth, leading to rapid mode dissipation and orbital decay. These dynamical (chaotic) tides may resolve several outstanding issues related to high-eccentricity migration. In particular, they could lead to rapid formation of eccentric WJs and increase the formation fraction of HJs. Combining with a proper treatment of spin-orbit coupling, they may also lead to significant changes in the predictions of the final spin-orbit misalignments in all high-eccentricity migration scenarios.

The main effort of our proposed research will be devoted to incorporating dynamical tides into two of most important classes of high-eccentricity migration scenarios: (1) Lidov-Kozai migration driven by stellar or planetary companions; (2) "secular chaos" resulting from interactions between three or more planets. We will use the secular equations of motion at the octupole-level [for (1)] and a newly developed Gaussian ring code [for (2)] to evolve the planet's orbits, and at the same time follow the evolution of the mode amplitudes (dynamical tides). The goal is to understand how dynamical tides affect the HJ/WJ formation efficiency and timescales, and compute the orbital properties of HJs and WJs produced in these scenarios. We will also investigate the dynamics of stellar spin, with the goal of predicting the spin-orbit misalignment distributions for different host stars and planets.

We will also carry out more exploratory studies on the physics of dynamical tides and the thermal evolution of giant planets (including dynamical tidal heating) undergoing high-eccentricity migration.

This proposal is relevant to NASA's Exoplanet Research Program goal of "Improve understanding of the origins of exoplanetary systems". The proposed research will also help enhance the science return of ongoing and future NASA space missions such as Kepler/K2 and TESS.

Michael Line/Arizona State University
Characterization of Transiting Exoplanet Atmospheres with High Dispersion Cross-Correlation Spectroscopy

The field of exoplanet atmospheres has matured enough to the point where we can begin to ask fundamental questions regarding planetary climate, composition, atmosphere-planet formation links , and provide context for understanding our own solar system planets. The community has leveraged the power of numerous ground and space based observatories to characterize a diverse range of planets ranging from hot Jupiters to terrestrial sized, potentially habitable worlds. Much of the atmospheric characterization work to date has focused on results from low dispersion spectroscopy (LDS) and photometry from space-based instruments like the Hubble and Spitzer Space Telescopes. While we owe much of our exoplanetary atmosphere insights from such observations, they are limited in the accessibility of certain molecules and atmospheric regions probed, due to low resolution and sparse wavelength coverage. JWST will solve many of these problems, however it is a limited resource and it is prudent that we have independent and robust alternative methods that leverage numerous ground-based facilities

An exciting emerging approach for characterizing atmospheres is high dispersion cross-correlation spectroscopy (HDCCS). HDCCS leverages the large number of molecular lines attainable at high resolutions (R>30,000) and large ground bases apertures to robustly detect molecules. This is the only method to have robustly detected carbon-based molecules in transiting exoplanet atmospheres. However, little work has focused on the ability to constraint the abundances of molecules, vertical temperature structures,

and other fundamental atmospheric properties from HDCCS data in a rigorous way. One of the primary challenges in doing so is placing the HDCCS within a robust atmospheric retrieval framework, a widely applied key tool in LDS data interpretation. Our team has recently pioneered placing HDCCS and LDS within in a common retrieval framework to maximize atmospheric constraints. Additionally, recently commissioned instruments such as CARMENES, GIANO, iSHELL, IGRINS, and ESPRESSO have greatly improved the prospects of atmospheric constraints from HDCCS observations.

We propose to leverage the power of HDCCS combined with bayesian atmospheric retrieval methodologies to:

- Determine previously undetermined Bayesian confidence intervals on atmospheric properties (molecular composition, thermal structures, elemental ratios) derived from current archival high-resolution datasets of transiting planets, such as those from VLT CRIRES and Keck NIRSPEC.
- Develop a unified bayesian retrieval framework that combines LDS (R<~5,000,e.g., HST, JWST) and HDCCS, as well as identify the strengths and weaknesses of each method.
- Investigate the potential constraints for molecules presumed to be present in temperate terrestrial planets and identify high resolution wavelength regimes that are most amenable to precision abundance constraints, with applications to the next generation of large telescopes like TMT and GMT.

We will explore these objectives within the context of all transit geometries and wavelength regimes, including transmission, emission, phase resolved, and reflected light. Our team is uniquely suited to accomplish these goals both from a HDDCCS and LDS data analysis perspective as well as the theoretical modeling. The proposed work will directly address the NASA XRP goal of understanding exoplanetary systems by refining and stress testing the key tools used to “characterize exoplanets and their atmospheres in order to inform target and operational choices for current NASA missions, and/or targeting, operational, and formulation data for future NASA observatories”. Application of this unified framework will allow us to gain a better idea of the data required to “understand the chemical and physical processes of exoplanets (including the state and evolution of their atmospheres)”.

Jack Lissauer/NASA Ames Research Center
Models of the Formation and Structure of Exo-Neptunes with Improved Physics

Science Goals and Objectives:
We propose to investigate, through numerical modeling, some outstanding problems in the theory of the formation of warm (sub-)Neptunes, which Kepler has shown to be common in our galaxy. Heavy elements dominate the composition of these planets by mass, but light gases fill most of their volumes. The proposed work will account for important physical processes heretofore neglected and, thereby, provide a much more realistic model for the formation and evolution of warm (sub-)Neptunes. Results from

these simulations will provide constraints on the interior structure (i.e., density, temperature, etc.) of the accreted planet, after billions of years of evolution, which can be compared with mass and radius observations to deduce planetary compositions of many of the planets found by Kepler and TESS. During the early stages of planetary accretion, when a rocky core reaches around an Earth mass, the basal temperature of the hydrogen/helium atmosphere above this growing core can already exceed a few thousand degrees, sufficient to allow evaporation of accreted planetesimals (and the release of vapor rock) within the envelope. This may affect the growth of the planet, primarily by increasing the mean molecular weight of the envelope (hence reducing the pressure scale height), and it may also produce a wider range of possible outcomes for planet formation than those previously studied. The consequences may be partially preserved throughout the subsequent evolution, and influence the internal structure of the planets observed today. To study the effects of this process, we will compute the amount of mixing of the constituents within the planets during their growth. This additional physics will be incorporated into detailed numerical models of the concurrent accretion of solids and gas, including an improved treatment of the interactions of the growing planets with the surrounding protoplanetary disk.

The proposed work will address the following questions:

1) How much condensible (within protoplanetary disks) material vaporizes and remains mixed with gas-rich planets' H and He 'envelopes'? Do such planets retain well-defined heavy element 'cores', or are their lower 'envelopes' so enriched in heavy elements that the compositional gradients are gradual?
2) Can the sub-Neptune-type planets, to date observed primarily within ~ 1 AU from their star, be best explained through formation at greater distances followed by orbital migration, or by in situ formation?
3) As gas-rich planets cool and shrink, how do their moments of inertia and rotation rates evolve?

Methodology:
Accretion of solids will be modeled using the PSI Multizone Code. The internal structure and evolution of each planet will be modeled with an adapted 1D stellar evolution code. Gas accretion and loss will be followed by accounting for thermal processes within the planet, tidal forces and photoevaporation.

Relevance to NASA's Exoplanets Research Program:
The proposed investigation will 'improve understanding of the origins of exoplanetary systems' by providing a substantially more realistic physical model of the formation of intermediate-size planets, found by Kepler and predicted to be found in large numbers by TESS. In particular, much improvement is expected by including the mixing of light and heavy elements within the planet and by our treatment of the final stages of accretion when the planets' ultimate masses and heavy-element contents are determined. We will determine whether or not the mass-radius distribution of characterized exoplanets suggests that they have substantial components of astrophysical ices in addition to rocky compounds and H/He. Our results will therefore also help 'understand the chemical and physical processes of exoplanets (including the state and evolution of their ... interiors'

Stephen Lubow/Space Telescope Science Institute
Planet-Disk Evolution Around Misaligned Binaries

One of the major achievements of the Kepler mission was the discovery of transiting circumbinary planets. Such planets likely form in circumbinary disks. Observations indicate that such disks may form misaligned with respect to the orbital plane of the central binary. We propose to first study the evolution of such disks for a wide range of possible initial masses and inclinations and for a variety of eccentricities of the central binary. For small inclinations, evolution ultimately towards coplanarity is expected. However, for eccentric orbit binaries, the evolution involves secular tilt oscillations towards and away from coplanarity before coplanarity is achieved. For larger inclinations, we have recently found that an initially moderately misaligned circumbinary protoplanetary disk around an eccentric binary can evolve to an orientation that is perpendicular to the orbital plane of the binary (polar alignment). We propose to continue our studies of the tilt disk evolution of circumbinary disks. For planets formed in such disks, we will investigate their orbital evolution due to planet-disk and planet-binary interactions. We propose to investigate these processes for a range of binary and disk parameters by means of analytic, one-dimensional, and three-dimensional simulations. The results will provide insights into the origin and current state of circumbinary planets.

Dimitri Mawet/California Institute of Technology
Direct imaging studies of the birth and early evolution of giant planets

Recent ground-breaking ALMA observations of protoplanetary disks in the mm continuum have revealed an impressive gallery of ring substructures, gaps, and spiral density waves. Axi-symmetric structures can be formed via three distinct mechanisms: magnetized disk evolution, condensation fronts at the snow lines, and dynamical interactions with forming planets. Spiral density waves on the other hand are expected to be excited by planet-disk interactions or by gravitational instabilities. The ALMA detected structures are short lived, lasting only for the first few Myr before fading into much more tenuous debris disks. This dramatic evolution from the protoplanetary phase, through the transition disk phase, up to debris disk sets a complex stage for the formation of planetary systems, which is thought to be governed by the assembly and migration of gas and ice giants. Here we propose to survey a selected sample of prominent protoplanetary disks in search of newborn giant planets, their accretion signatures, and evidence of planet-disk interactions. For that, we will use the most powerful telescope and instrument in the world, the Keck II adaptive optics system, which has been recently upgraded with a unique combination of mid-infrared (L and M bands; 3-5 Âµm) vortex coronagraphs and an infrared pyramid wavefront sensor. Both modules give us unprecedented sensitivity to planets in star forming regions and targets usually deemed too faint for adaptive optics studies. For the youngest targets, our observations are particularly sensitive to the thermal emission from circumplanetary disks, which, if detected, will help us characterize planet accretion in detail through multi-color and

spectroscopic measurements. In some favorable cases, our observation will reveal disk structures in scattered light. When combined with ALMA images, placed in the context of the SED at other available wavelengths, and analyzed with radiate transfer codes such as MCFOST, our images will be a powerful probe of disk properties, including their 3D geometry, gains size distribution, and composition. Our survey will test the leading theories for planet formation and shed light on substructure formation mechanisms.

Lisa Prato/Lowell Observatory
Finding the Youngest Exoplanets

Despite the stunning wealth of data provided by the discovery of thousands of planets spanning a surprisingly broad parameter space, we know very little about young planets. To accurately advance our understanding of the processes which govern planet formation, migration, and evolution, we must identify and study young planets themselves.

In 2016 we published the extraordinary identification of a ~12 Jupiter mass object in a 9 day period orbit in the 2 Myr old classical T Tauri system CI Tau, representing the first unambiguous discovery of a young star + disk + short-period planet known. The key to the success of this work was the application of intensive IR high-resolution spectroscopy. Our original survey was limited to high-resolution optical spectroscopy by virtue of having adequate access to large time allocations on the McDonald Observatory 2.7-meter telescope. However, stellar activity effects are a function of wavelength and have a much larger impact on RV amplitudes in the optical than in the IR, whereas gravitationally-induced RV variations show the same amplitudes at all wavelengths. Thus the ideal approach to an RV survey of active, spotted young planets is to use IR spectroscopy for the primary observations with optical follow up as needed.

We are proposing for support of our young exoplanet RV observations using the transformational combination of the IGRINS IR spectrograph and Lowell Observatory's 4.3-meter Discovery Channel Telescope (DCT). In collaboration with the University of Texas, McDonald Observatory, and the Korean Astronomy and Space Science Institute, IGRINS is in residence at the DCT for 6 months per year over through 2019. The first visits covered September 2016-February 2017 and August 2017-January 2018. IGRINS is scheduled to return to the DCT in September 2018, and possibly again in future years (TBD). Prior to this deployment at the DCT, we obtained substantial survey data with IGRINS at the 2.7-meter telescope at McDonald Observatory. These spectra from McDonald, combined with new data obtained with generous time allocations (28 nights in the 2016-2017 season and 23 in the 2017-2018 season) on the DCT, are expediting our unprecedented IR survey for substellar objects around young stars. To date, at the DCT we have obtained minimum 3-4 spectra for each of our 140 target stars; for a subsample we have dozens of observations. IGRINS third visit will be used for intensive observations of promising candidate exoplanet host stars. A new, high-resolution optical spectrograph is being commissioned at the DCT by Yale University, potentially providing near-simultaneous optical spectroscopy in the future; we will use the McDonald 2.7 meter telescope for optical spectroscopy in the near term.

The relatively short-period giant planets we are sensitive to are of fundamental importance in part because of their role in the dynamics of the inner 1 AU, the terrestrial planet-forming region. Detections of planets around stars with primordial disks are especially interesting because they provide a direct link between the host disk and the exoplanet properties. With JWST, it will be possible to study disk composition and structure in systems with planets for comparison with systems which lack giant planets, potentially providing a predictive tool for planet formation. Our proposed work provides unprecedented targets for JWST campaigns. Furthermore, our use of K2 data products to understand and disentangle stellar rotation and activity from exoplanet signatures adds tremendous value to both data sets.

This research is directly related scientifically to the NASA Strategic Objectives "1.5 Ascertain the ... origin, and evolution of the solar system" and "1.6 Discover how the universe works, explore how it began and evolved" and to Objective "3.1 Attract and advance a highly skilled, competent, and diverse workforce, cultivate an innovative work environment".

Stephen Shectman/Carnegie Institution of Washington
A Southern Hemisphere RV Follow-up Program for TESS

Science Goals and Objectives: Numerous formation theories have been proposed for exoplanets with radii between the 1-3 Rearth, the most common in the Galaxy within P<100 days. Recent observations of a radius gap suggest these small planets fall into two groups, super-Earths and sub-Neptunes, but whether they represent a continuous population shaped by post-formation processes or two distinct populations that formed differently is still unclear. Our program on following up the exoplanets discovered by TESS in the Southern Hemisphere will address this issue, specifically by answering three well-defined questions:

- How do planetary bulk densities depend on stellar insolation? While the period dependence of the radius gap is consistent with volatile envelope evaporation, this process also depends on surface gravity. Obtaining masses for planets between 1.5 and 2.5 Rearth at a range of insolation fluxes is necessary to test if photoevaporation has caused the observed gap, and whether the bimodality seen in planet radii extends to the planet mass-radius-insolation flux phase space.

- How do planetary bulk densities depend on host star composition? For the ~100 planets smaller than 3 Rearth with mass and radius constraints, there is a spread in mass at any given radius that is not due entirely to measurement uncertainty. This may indicate a diversity in solid interior composition, and by proxy the host star composition. We will measure and compare the densities of a larger sample of small planets to detailed host star abundances to understand the role of composition in the planet mass-radius relationship.

- How do planetary bulk densities depend on system architecture? High eccentricities of transiting planets and/or mutual inclinations between sibling planets point towards dynamically active evolution, versus in situ formation or smooth disk migration. Determining transiting planet eccentricities, whether they have non-transiting siblings, and how planetary system architectures are related to planet bulk density, will help distinguish whether super-Earths and sub-Neptunes have different formation mechanisms.

Methodology: We propose a comprehensive follow-up program to go from planet candidates detected in TESS light curves to ~30 confirmed and well-characterized planets. Our characterization will include RV-measured masses, with ~60 RV observations per vetted system, host star abundances, and constraints on longer period non-transiting planets. Critically, we will select our sample with a time-invariant merit function from which we can robustly infer population-based trends to answer our proposed questions. Our team members have access to and expertise in using resources for all of the required steps. We plan to share our RV observing plans on the TFOP platform to facilitate coordination and collaboration with other teams.

Relevance: This proposal directly addresses the key XRP objectives, including "determination of compositions, dynamics, ...of [exo]planets" and "characterization of other planetary systems." Our investigation is closely tied to the TESS mission and will help maximize its science return through confirming planets candidates and further characterizing their masses, host stars, and non-transiting sibling planets. This work will help inform the target selection for current (HST, \textit{Spitzer}) and future (JWST, LUVOIR/HabEx) NASA observatories.

Rachel Street/Las Cumbres Observatory Global Telescope Network
Understanding exoplanets detected by microlensing

In trying to understand planet formation, one of the most powerful tools we have is to compare the distributions of the physical and orbital properties of the planets discovered with those predicted by formation and evolutionary models. For this to be effective, we need a complete census of planetary systems at all masses and orbital separations. But no one survey technique is sensitive to the whole parameter space. Kepler provided a landmark catalog of planets at small orbital radii around their host stars, complementing the results of other mostly ground-based projects, but there is a significant gap in the detected population of low-mass planets at separations of few-10 AU, where most detection techniques suffer a dramatic drop in efficiency and/or sensitivity. Microlensing offers a way to bridge this gap, and so is one of the goals of the forthcoming WFIRST Mission.

Preparatory work for the WFIRST microlensing survey is already underway. A major element of it will be to develop tools capable of analyzing the large resulting dataset and detecting microlensing events within, while carefully distinguishing between false positives and systematics. This presents a number of challenges, since the analysis of just

one binary lensing event can be computationally intensive, and there is a marked shortage of people (~10) in the US who specialize in this subject. Existing software tools for this task are mostly proprietary, and have limitations which mean they will not scale to process the WFIRST dataset in a timely manner.

We will address this challenge by developing a two-stage detection and classification system for the WFIRST Bulge survey data using a combination of machine learning techniques. The first stage builds on prototype random-forest microlensing/variable star detection software already developed by our team to distinguish astrophysical signals from systematics or false positive detections. We propose to combine this with a second stage which will leverage recent progress in Deep Learning software to analyze the lightcurves of binary lensing events and identify all possible models which are consistent with the data. This will address a long-standing problem in the modeling of binary lenses, for which there are a number of known degeneracies.

The effectiveness of machine learning systems depends critically on the quality and quantity of the data used to train the system. We will to leverage a number of public photometric catalogs to help to train the system, and apply it to analyze data from the ongoing Microlensing Key Project at LCO, ROME/REA, a high cadence, tri-band optical survey for microlensing events in the Galactic Bulge. Our team was awarded 2650 hrs/yr for 3yrs starting in 2017 for this survey, which is currently in its second observing season. We will release a complete catalog of the imaging and photometry from ROME/REA for community use through a NASA archive. We will also conduct simulated-event injection tests to evaluate the algorithm's performance and detection statistics. Once the algorithm is applied to WFIRST data, this analysis will enable us to calculate the true planet frequency. All software developed through this proposal will be thoroughly tested and documented, ahead of its public release for community use.

This proposal is highly responsive to the aims of the Exoplanets Research Program, since it will discover and characterize planetary systems and advance preparations for the WFIRST Mission. It will also provide a valuable resource for a wealth of stellar astrophysics.

Sloane Wiktorowicz/The Aerospace Corporation
Direct Detection of Exoplanet Cloud Particles with Polarimetry

Many short-period, transiting hot Jupiter exoplanets appear to harbor cloud particles in their atmospheres. However, since most techniques employed to characterize the daysides of exoplanet atmospheres utilize only the intensity component of the electric field, degeneracies in the physical models may make it difficult to distinguish cloud particle size and chemical composition. In contrast, the linear polarization of sunlight scattered by Titan and Venus has long indicated the presence of fractal aggregate haze particles and concentrated sulfuric acid clouds, respectively.

After 10 h of Gemini North POLISH2 observations, we have discovered polarized light scattered by the transiting hot Jupiter WASP-12b in B band, where maximum polarization occurs near quarter phase as predicted for scattering by small particles. Assuming a pure Rayleigh scattering atmosphere, this 5 sigma detection of scattered light implies a B-band geometric albedo of 0.128 (+0.022, -0.013, 1 sigma) and a single scattering albedo of 0.492 (+0.057, -0.036), which is the second most tightly constrained geometric albedo to date. These data reject a clear atmosphere with no absorber (0.8 albedo) for WASP-12b with 9 sigma confidence and require absorption by particles. From our polarized radiative transfer models that include the dependence of particle size distribution and index of refraction on the polarization phase curve, our measurements are consistent with corundum (Al2O3) cloud particles with effective sizes between 0.035 and 0.11 microns (2 sigma confidence) and marginally consistent with perovskite (CaTiO3) particles with effective sizes between 0.0089 and 0.015 microns. The presence of small cloud particles is consistent with the Rayleigh scattering slope from transmission spectroscopy, and corundum and perovskite are the two leading candidate cloud species in this planet. However, the effective perovskite size range from polarimetry is mutually exclusive with that from transmission spectroscopy, which eliminates perovskite as a candidate and provides the direct detection of corundum cloud particles in the WASP-12b upper atmosphere.

We propose to perform Gemini POLISH2 observations of HD 189733b and HD 209458b to identify the cloud particle composition and size distribution in their upper atmospheres. Specifically, HD 189733b is hypothesized to harbor MnS clouds, while HD 209458b is expected to harbor MgSiO3 and Mg2SiO4 clouds. Additionally, polarization from small particles tends to peak at quarter phase, when a cold terminator is in view. Cloud condensation is maximized at these terminators. We therefore propose to observe these planets, as well as complement our existing WASP-12b observations, to determine whether particle properties change between hemispheres. Such inhomogeneous longitudinal variations are present in Kepler-7b, and our proposed measurements will test the possibility of their existence in HD 189733b, HD 209458b, and WASP-12b.

Karen Willacy/Jet Propulsion Laboratory
Chemical tracers of vortices in disks

ALMA and VLA observations show large azimuthal asymmetries in the millimeter emission from many transitional disks' outer regions. The leading explanation is that these asymmetries arise from millimeter-sized dust trapped in giant vortices. Dust emission alone cannot confirm this identification but potentially molecular line observations could if the different physical conditions in the vortex result in different chemistry compared to the background disk. We propose to investigate whether molecules make good tracers of vortices, their properties and their drivers. The chemical effects induced by a vortex will depend on the relative timescales of the chemistry and the dynamics, and on the contrast between the physical conditions in the vortex and the disk. Chemical changes can also be induced by grain growth and changes to the dust/gas

mass ratio in the vortex. Compared to the background disk there should be a different and potentially distinguishable distribution of species within a vortex.

We will trace the compositional changes induced by a vortex in a disk by coupling a chemical reaction network to analytic models of vortices. For a range of vortex properties (aspect ratio, size and distance from the star) we will determine the characteristics of the dust within a vortex (the dust size distribution and the dust/gas mass ratio), and the best chemical probes of vortex conditions. We will also model two observed disks with both asymmetrical dust distributions and apparently associated molecular lines to determine whether the observed differences are a result of vortex properties. We will generate continuum and line emission maps of the vortex/disk system for comparison with observations and predict chemical probes of vortices to guide future observations.

We will choose a subset of the analytic models with the strongest chemical contrasts between vortex and disk to carry out a more detailed study of the vortex structure using numerical hydrodynamics. We will take into account the 3-D motions of material within the vortex, and the changes in temperature and irradiation caused by differences in scale height between the vortex and the disk. We will again generate continuum and line emission maps and will evaluate whether the analytic models provide an adequate description of the vortex chemical structure.

Since vortices can concentrate dust particles within them, they may be regions of enhanced planetesimal formation. If this happens then chemical changes in a vortex will be reflected in the composition of any planetesimals that form within it. We will explore the variation of ice composition with vortex parameters to determine whether different types of vortices result in different planetesimal compositions, e.g. in different C/O ratios.