Exoplanet Research Program
Abstracts of Selected Proposals
(NNH16ZDA001N-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 7, 2016, 22 proposals were selected for funding.

Gaspar Bakos/Princeton University
Finding and Characterizing a Large and Diverse Population of Transiting Exoplanets with HATSouth in Support of NASA Space Missions

The goal of this proposal is to utilize the fully-operational HATSouth global telescope network in support of the NASA K2, TESS and JWST missions, with the aim of broadening the discovery space of these missions, and jointly or separately discovering and characterizing a large number of interesting transiting exoplanets around stars bright enough to enable detailed follow-up study by facilities including JWST. Here we place a particular emphasis on classes of planets that have not been well-studied to date: namely, Neptune-size or smaller planets, planets with orbital periods >10 days (or longer), and planets around M dwarf stars or A-type stars.

We will achieve this goal by using the HATSouth global telescope network over a 4 year period to carry out photometric time-series observations of 15% of the Southern sky, yielding several month long, nearly continuous light curves for approximately 4 million stars in the magnitude range $9.5<r<15.5$, at substantially higher spatial resolution than TESS, and with a photometric precision that is comparable to TESS for many stars. Here we take advantage of the global nature of HATSouth to provide time-coverage that is as close to space-like as possible from the ground. We will follow an observing strategy that provides maximum support for the K2 and TESS missions. First we will scan Southern K2 fields to submit candidate transiting planet systems for high-precision monitoring by K2, and then we will monitor fields in the TESS 27-day observing window to extend the time-coverage of these regions of the sky, and enable the discovery of planets with periods longer than 15 days through a joint analysis of the TESS and HATSouth light curves. We will combine the HATSouth light curves with space-mission data when available, search these data for transiting planet signals, and carry out a large follow-up program for approximately 20% of the candidates to confirm and characterize approximately 100 planets. The higher resolution HATSouth data will also be used to rule out hundreds of blended eclipsing binary systems that are selected as planet candidates in the lower spatial resolution TESS data. All data from this project will be made public. This includes all HATSouth light curves already generated and those which will be generated through observations carried out during the period of performance.

This proposed effort will contribute significantly to the NASA K2, TESS and JWST missions, and to the exploration of exoplanets in the Galaxy. By pre-selecting candidate planets for monitoring by K2 we will be able to increase the number of transiting planets

observed at high-precision by this mission by as much as 20 percent. The 3 arcsecond spatial resolution of HATSouth will allow us to rule out hundreds of blended eclipsing binary false positives selected as planet candidates by TESS, while the extended time coverage of HATSouth will allow us to find dozens of long period planets through a joint analysis of HATSouth and TESS data that would not be found by TESS or HATSouth alone. The HATSouth data will also be used to confirm many candidate transit signals found by TESS around intrinsically faint K and M dwarf stars. Moreover, our follow-up observations will contribute to the overall TESS follow-up effort. Continued HATSouth observations, by themselves, will yield approximately 500 transiting planet detections, in addition to the approximately 400 planets already identified by HATSouth, and the 700 expected to be identified in data that have been collected. We expect our follow-up effort to confirm and provide a detailed characterization of approximately 100 of these, including dozens of planets that are Neptunes or Super-Earths, that have periods longer than 20 days, or that are orbiting M dwarf stars. A significant fraction of these will be around stars with K < 12, allowing in depth follow-up studies, including atmospheric characterization with JWST.

Ian Dobbs-Dixon/NYUAD
Modeling Exoplanetary Atmospheres using BART, TEA, and Drift-RHD; Theoretical studies and Observational Implications

The explosion in the number of exoplanets detected to date has revealed a surprising diversity. When attempting to model this diversity, it is crucial to account for the uncertainties resulting from our limited knowledge of chemical, dynamical, and cloud formation processes in their atmospheres. Combining a retrieval technique with theory-driven models is a particularly promising way to address these processes and constrain a physically plausible atmospheric structure. In particular, a detailed micro-physical treatment of clouds and the longitudinal and latitudinal assessments of temperature and chemical profiles, have yet to be addressed in the field.

Our team members are experts in radiative-hydrodynamic modeling (Dr. Ian Dobbs-Dixon), cloud kinetics (Dr. Christiana Helling), retrievals and thermo-equilibrium chemistry (Dr. Jasmina Blecic), and observational diagnostics and predictions (Dr. Thomas Greene). The key goals of this proposal are to extend our understanding of the 3D atmospheric structure of gas-giant exoplanets by coupling state-of-the-art self-consistent models together with a retrieval framework to 1) address cloud kinetics in retrievals, 2) assess 3D temperature and chemical structures in retrievals, 3) model a suite of well-observed planets within the framework of our models, and 4) make observational predictions for current and future NASA missions.

To address these goals we have developed a number of tools: Drift-RHD, TEA, BART, and OBS. Drift-RHD solves both the 3D radiative-hydrodynamic equations and a time dependent kinetic cloud model. TEA, Thermochemical Equilibrium Abundances, calculates abundances of chemical species present in the atmosphere. BART, a Bayesian Atmospheric Radiative Transfer code, is a statistical retrieval framework to explore the

parameter space of atmospheric chemical abundances and thermal profiles. OBS is a suite of tools developed to simulate observations. Though these tools exist and have been utilized independently in numerous published papers, further work is needed to couple them self-consistently.

Our theoretical studies focus on a number of objectives. We will start by incorporating our kinetic, non-equilibrium cloud model within BART, allowing us to obtain a consistent solution for cloud characteristics. We will further test simple parameterizations against the full solution to explore the reliability of simpler models. Utilizing Drift-RHD, we will explore the role of horizontal advection on cloud distribution, investigate the validity of 1D retrievals by comparing them to self-consistently generated 3D models, and develop a retrieval framework for wavelength-dependent phase-curves. TEA will be enhanced with additional databases and the inclusion of condensates, providing realistic initial cloudy-model for retrievals.

To explore the importance of equilibrium chemistry and exclude non-plausible chemical compositions (often the outcome of many retrieval approaches) we will relax the assumption of non-equilibrium chemistry by utilizing an analytical chemical equilibrium approach in BART. To address observations, our OBS suit for generating synthetic observations will be adapted to interface with our models, allowing us to both compare to existing observations and make predictions for future observations. With these tools, we are particularly well suited to understand discriminants between classes of models and identifying which particular set of observations could most readily distinguish cloud constituents and temperature features.

The proposed research is directly relevant to the Planetary Science and Astrophysics goals through furthering our understanding of compositions, dynamics, energetics, and chemical behaviors of exoplanetary atmospheres. In addition, to maximize NASA's investment and encourage open access, we have and will continue to make all of our codes public and available to the community throughout the course of the research.

Daniel Fabrycky/University of Chicago
Gigayear Instabilities in Planetary Systems

One of the biggest modern discoveries about the Solar System is that it is chaotic (Laskar 1989, 1994). On million-year timescales, nearby trajectories exponentially diverge; on billion-year timescales, planets can develop large eccentricities and even collide. This is possible because our planets interact with enough energy and with the right (secular) timescales. This has the potential to put the planet Mercury on an unstable orbit in the future, before the Sun exhausts its fuel. Currently, as a standard step in the analysis, exoplanet observing teams check whether the planetary systems they are discovering are stable. This usually involves a few-Megayear numerical integration, and the system usually passes that test. However, the signatures of continuing instability have not been looked for in the exoplanet population, nor has its implications for planetary formation and evolution been fully recognized.

We will study several specific evolutionary scenarios in which instability may manifest only on gigayear timescales, i.e. midway through the lives of the host stars. This is relevant to the solicitation in that it characterizes the dynamics of exoplanetary systems.

In the first project, we will compare N-body, numerically-calculated secular, and Fourier-expansion secular theories to determine what essential ingredients go into the conclusion that a general planetary system is chaotic. We will apply these tools to specific realizations of Kepler-discovered close-in planetary systems consisting of three or more Neptunes or super-Earths, which is the most populous known exoplanet population. We will thus find the common ailments afflicting middle-age planetary systems.

In the second project, we will consider how planets might get stranded in their Kuiper and Oort clouds during early system evolution, only to destabilize the inner system later on. Various investigators have wondered whether the Solar System is accompanied by a massive planetary companion, including a prominent proposal of one earlier this year. We will use N-body and analytic secular methods to study planet-planet scattering in the context of stellar birth clusters. External torques may lift the periastra of scattering planets, placing them in the comet cloud, and we will calculate the probability for such planets to return on gigayear timescales.

In a final project, we will set our gaze on the Alpha Centauri system. As is well-known, it is a triple stellar system with a very distant third star (Proxima Centauri). Observers continue to debate whether it hosts a planet and whether or not a space mission should be dedicated to this system. As theorists, we propose to calculate the probability that Proxima has, or will, substantially alter the orbit of the binary, and what dynamical effect this has on a potential planetary system. If the binary was more circular in the past, then planet formation was easier around each star. If the binary is getting more eccentric now, it can destabilize its planetary system, even at this late date. This project will also use N-body and analytic secular methods.

Joseph Harrington/University of Central Florida
Atmospheric Retrievals from Exoplanet Observations and Simulations with BART

This project will determine the observing plans needed to retrieve exoplanet atmospheric composition and thermal profiles over a broad range of planets, stars, instruments, and observing modes.

Characterizing exoplanets is hard. The dim planets orbit bright stars, giving orders of magnitude more relative noise than for solar-system planets. Advanced statistical techniques are needed to determine what the data can - and more importantly cannot - say.

We therefore developed Bayesian Atmospheric Radiative Transfer (BART). BART explores the parameter space of atmospheric chemical abundances and thermal profiles using Differential-Evolution Markov-Chain Monte Carlo. It generates thousands of candidate spectra, integrates over observational bandpasses, and compares to data, generating a statistical model for an atmosphere's composition and thermal structure. At best, it gives abundances and thermal profiles with uncertainties. At worst, it shows what kinds of planets the data allow. It also gives parameter correlations.

BART is open-source, designed for community use and extension (http://github.com/exosports/BART). Three arXived PhD theses (papers in publication) provide technical documentation, tests, and application to Spitzer and HST data. There are detailed user and programmer manuals and community support forums.

Exoplanet analysis techniques must be tested against synthetic data, where the answer is known, and vetted by statisticians. Unfortunately, this has rarely been done, and never sufficiently. Several recent papers question the entire body of Spitzer exoplanet observations, because different analyses of the same data give different results. The latest method, pixel-level decorrelation, produces results that diverge from an emerging consensus.

We do not know the retrieval problem's strengths and weaknesses relative to low SNR, red noise, low resolution, instrument systematics, or incomplete spectral line lists. In observing eclipses and transits, we assume the planet has uniform composition and the same temperature profile everywhere. We do not know this assumption's impact.

While Spitzer and HST have few exoplanet observing modes, JWST will have over 20. Given the signal challenges and the complexity of retrieval, modeling the observations and data analysis is the best way to optimize an observing plan.

Our project solves all of these problems. Using only open-source codes, with tools available to the community for their immediate application in JWST and HST proposals and analyses, we will produce a faithful simulator of 2D spectral and photometric frames from each JWST exoplanet mode (WFC3 spatial scan mode works already), including jitter and intrapixel effects. We will extract and calibrate data, analyzing them with BART. Given planetary input spectra for terrestrial, super-Earth, Neptune, and Jupiter-class planets, and a variety of stellar spectra, we will determine the best combination of observations to recover each atmosphere, and the limits where low SNR or spectral coverage produce deceptive results.

To facilitate these analyses, we will adapt an existing cloud model to BART, add condensate code now being written to its thermochemical model, include scattering, add a 3D atmosphere module (for dayside occultation mapping and the 1D vs. 3D question), and improve performance and documentation, among other improvements.

We will host a web site and community discussions online and at conferences about retrieval issues. We will develop validation tests for radiative-transfer and BART-style

retrieval codes, and provide examples to validate others' codes. We will engage the retrieval community in data challenges. We will provide web-enabled tools to specify planets easily for modeling. We will make all of these tools, tests, and comparisons available online so everyone can use them to maximize NASA's investment in high-end observing capabilities to characterize exoplanets.

Brian Jackson/Boise State University
Unstable Roche-Lobe Overflow of Gaseous Planets

The discoveries of more than 100 roughly Earth-sized bodies with orbital periods less than 1 day, ultra-short-period planets or candidates (USPs), have challenged planet formation theories, and evidence suggests USPs may be the remnants of gaseous planets that shed their atmospheres. Indeed, many hot Jupiters are near Roche-Lobe overflow (RLO), and tidal decay can push them the rest of the way in. Recent work has shown stable RLO (atmospheres lost via a steady outflow and thin accretion disk) probably cannot produce USPs on its own but suggested unstable RLO (atmospheres quickly shed on dynamical timescales) may. In fact, stable RLO may drive overflowing hot Jupiters into unstable RLO, and by analogy with the common-envelope binaries, the core that remains can drive off the gaseous envelope at the cost of its orbital energy. Well-established mass-radius relations for gaseous planets, coupled to simple energy and angular momentum considerations, provide a connection between the observed masses and periods for USPs and their putative progenitor gaseous planets, with few free parameters. We propose to investigate the hypothesis that USPs originate through tidal decay and a combination of stable and unstable Roche-lobe overflow of short-period gaseous planets through the following studies:

--We will explore the planetary masses, orbital periods, etc. that produce unstable RLO using the Modules for Experiments in Stellar Astrophysics (MESA) suite.

--We will relate the observed periods and masses of USPs to their putative progenitor masses and periods to see whether they are consistent with the unstable RLO hypothesis.

This proposal is directly relevant to the Exoplanets Research Program since it seeks to “understand the ... physical processes of exoplanets” and “improve understanding of [their] origins” through “theoretical studies ... and modeling'”. We also expect that it will have broad impacts on a variety of astrophysical topics:

--Ultra-short period planets could provide a glimpse inside gas giants. If our study corroborates the unstable RLO hypothesis, the properties of USPs may represent those of gaseous planet cores, which are almost entirely unconstrained. Even in our own solar system, estimates of the core masses for Jupiter (between 0 and 14 Earth masses) and Saturn (between 8 and 25 Earth masses) have large uncertainties. The upcoming Juno mission will clarify the situation for Jupiter, but it's unclear whether these constraints will directly bear on other planetary systems.

--The TESS mission will probably find hundreds of ultra-short-period planets. The Transiting Exoplanet Survey Satellite (TESS) will launch in 2017 and look for short-period rocky planets around 500,000 nearby stars. Roughly 0.1% of Sun-like stars host USPs, so TESS should find hundreds of USPs. These planets would be ideal for follow-up, and a clear framework for their origins would motivate and guide additional TESS observations.

--Even if we show they are not remnants of gaseous planets, ultra-short-period planets may serve as probes of the innermost protoplanetary gas disk and betray the presence of additional planets in their host systems. As we discuss below, one other obvious origin scenario involves dynamical interactions in a multi-planet system. Many USPs do not have observed siblings, so this scenario requires that there are additional, unseen planets in those systems. The exact location of USPs may be set, in part, by the inner edge of their maternal gas disk, a sensitive function of the host star's youthful properties.

Daniel Jontof-Hutter/University of Pacific

The Constraint of Coplanarity: Compact multi-planet system outer architectures and formation.-UP

The Kepler mission discovered 92 systems with 4 or more transiting exoplanets. Systems like Kepler-11 with six “mini-Neptunes” on orbital periods well inside that of Venus pose a challenge to planet formation theory which is broadly split into two competing paradigms. One theory invokes the formation of Neptunes beyond the “snow line”, followed by inward migration and assembly into compact configurations near the star. The alternative is that low density planets form in situ at all distances in the protoplanetary nebula. The two paradigms disagree on the occurrence of Jovian planets at longer orbital periods than the transiting exoplanets since such massive planets would impede the inward migration of multiple volatile-rich planets to within a fraction of 1 AU.

The likelihood of all the known planets at systems like Kepler-11 to be transiting is very sensitive to presence of outer Jovian planets for a wide range in orbital distance and relative inclination of the Jovian planet. This can put upper limits on the occurrence of Jovian planets by the condition that the six known planets have to have low mutual inclinations most of the time in order for their current cotransiting state to be plausible.
Most of these systems have little or no RV data. Hence, our upper limits may be the best constraints on the occurrence of Jovian planets in compact co-planar systems for years to come, and may help distinguish the two leading paradigms of planet formation theory.
Methodology.

We propose to use an established n-body code (MERCURY) to perform long-term simulations of systems like Kepler-11 with the addition of a putative Jovian planet considering a range of orbital distances. These simulations will test for which initial conditions a Jovian planet would prevent the known planets from all transiting at the same time. We will 1) determine at what orbital distances and inclinations an outer

Jovian planet would make the observed configuration of Kepler-11 very unlikely. 2) Test the effect of an undetected planet in the large dynamical space between Kepler-11 f and Kepler 11 g on our upper limits on a Jovian outer planet. 3) Repeat the analysis for all compact systems of 4 or more transiting planets with published planetary masses (including Kepler-79, Kepler-33, and Kepler-80) 5) Repeat the analysis for all systems of 4 or more transiting planets where the condition of long-term
orbital stability provides useful upper limits on planetary masses, using their orbital periods and an appropriate mass-radius relation. 6) Measure an upper limit on the occurrence rate of outer Jovian planets. If we find an occurrence rate significantly lower than the known occurrence rate of Jovian planets from RV surveys, this would be evidence in support of the migration model as Jovian planets are expected impede the assembly of compact coplanar systems of low-density planets close to the host star.
Relevance.

According to the XRP Solicitation, investigations are expected to directly support the goal of "understanding exoplanetary systems", by doing one or more of the following…"improve understanding of the origins of exoplanetary systems". This proposal will help distinguish between competing paradigms in planet formation with dynamical modeling, and hence will improve our understanding of the origins of exoplanetary systems. This proposal will in no way require analysis of archival Kepler data, and relies only on the published masses, radii and orbital periods of high muliplicity systems discovered by Kepler. Therefore, our proposal is not appropriate for ADAP.

Quinn Konopacky/University of California San Diego
Moderate Resolution Spectroscopy of Directly Imaged Exoplanets: Formation, Chemistry, and Clouds

More than twenty years after the discovery of the first planet orbiting a star other than the Sun, it is now clear that extrasolar planets are ubiquitous. With each new discovery, new questions are raised about planet formation and evolution that challenge commonly held assumptions. Few currently known exoplanets reside at separations beyond the ice line, forcing extrapolation when developing a theory to explain planet formation on all scales. In the next several years, the number of known exoplanets at wide separations will increase dramatically as a new era in exoplanet discovery commences - the era of direct imaging. By using techniques to achieve high angular resolution on large (8-10 meter) ground based telescopes, it is now possible to resolve and study the light coming from widely separated gas giant planets at unprecedented levels of detail.

Our group has pioneered observational and theoretical techniques that have provided spectra of directly imaged planets at resolutions and SNR that are rarely obtained for exoplanets. By using adaptive optics fed integral field spectrographs, we have extracted spectra at R~4000 in the near infrared, resolving individual molecular features from species such as water, carbon monoxide, and methane. These species have been used for detailed measurements of the ratio of carbon and oxygen in these planetary spectra. We propose to advance beyond these initial measurements and pursue a systematic program

of near-infrared spectroscopy covering a suite of directly imaged exoplanets at similarly high spectral resolutions.

Multiple surveys with newly commissioned instruments for direct imaging are now underway with the goal of substantially increasing the number of known directly imaged giant planets. The photometric and/or very low resolution spectroscopic data provided by these surveys are useful for rough planet characterization. Advancing our understanding of these planets, however, is best achieved through higher spectral resolution data, capable of resolving atomic and molecular lines. Depending upon the mode of planet formation, the differentiation of solids and gas in a protoplanetary disk may lead to elemental abundances that differ substantially from that of the host star. Subsequent migration or planetesimal accretion after formation can also lead to variation in the abundance of species such as carbon and oxygen. Our program will yield measurements of abundances and abundance ratios precise enough to study the early accretion history for a variety of giant planets.

We will provide a library of J, H, and K near-IR spectra for all observable directly imaged planets at these spectral resolutions. We will use these spectra to measure abundance ratios and search for higher atomic number species such as sodium and iron. Grids of models will be generated to test possible values of carbon, oxygen, and other metal abundances, in addition to properties such as non-equilibrium chemistry and cloud coverage. In order to assure that these models are not systematically yielding certain abundance values, we will test their predictions on a set of well-studied brown dwarfs with precisely measured masses, temperatures, and gravities.

The research proposed here is highly relevant to the NASA Exoplanets Research program. By probing the spectra of gas giant planets in unmatched detail, we seek to provide a fundamental understanding of the physical processes at work during the early stages of planet formation and the subsequent atmospheric evolution as a function of mass and age. The proposed research will complement current NASA exoplanet missions by investigating the relatively unexplored population of widely separated planets. We will also provide a framework for measuring atmospheric properties that will be applicable to planets discovered with upcoming NASA missions such as WFIRST-AFTA and JWST.

Marc Kuchner/NASA Goddard Space Flight Center
Disk Detective Follow-Up Program

As new data on exoplanets and young stellar associations arrive, we will want to know: which of these planetary systems and young stars have circumstellar disks? The vast all-sky database of 747 million infrared sources from NASA's Wide-field Infrared Survey Explorer (WISE) mission can supply answers. WISE is a discovery tool intended to find targets for JWST, sensitive enough to detect circumstellar disks as far away as 3000 light years. The vast WISE archive already serves us as a roadmap to guide exoplanet

searches, provide information on disk properties as new planets are discovered, and teach us about the many hotly debated connections between disks and exoplanets.

However, because of the challenges of utilizing the WISE data, this resource remains underutilized as a tool for disk and planet hunters. Attempts to use WISE to find disks around Kepler planet hosts were nearly scuttled by confusion noise. Moreover, since most of the stars with WISE infrared excesses were too red for Hipparcos photometry, most of the disks sensed by WISE remain obscure, orbiting stars unlisted in the usual star databases.

To remedy the confusion noise problem, we have begun a massive project to scour the WISE data archive for new circumstellar disks. The Disk Detective project (Kuchner et al. 2016) engages layperson volunteers to examine images from WISE, NASA's Two Micron All-Sky Survey (2MASS) and optical surveys to search for new circumstellar disk candidates via the citizen science website DiskDetective.org. Fueled by the efforts of > 28,000 citizen scientists, Disk Detective is the largest survey for debris disks with WISE. It has already uncovered ~4000 disk candidates worthy of follow-up.

However, most host stars of the new Disk Detective disk candidates have no known spectral type or distance, especially those with red colors: K and M stars and Young Stellar Objects. Others require further observations to check for false positives. The Disk Detective project is supported by NASA ADAP funds, which are not allowed to fund a major observational follow-up campaign.

So here we propose a campaign of follow-up observations that will turn the unique, growing catalog of Disk Detective disk candidates into a reliable, publically-available treasure trove of new data on nearby disks in time to complement the upcoming new catalogs of planet hosts and stellar moving groups. We will use automated adaptive optics (AO) instruments to image disk candidates and check them for contamination from background objects. We will correlate our discoveries with the vast Gaia and LAMOST surveys to study disks in associations with other young stars. We will follow up disk candidates spectroscopically to remove more false positives. We will search for cold dust around our disk candidates with the James Clerk Maxwell Telescope (JCMT) and analyze data from the Gemini Planet Imager (GPI) to image young, nearby disk candidates. This follow up work will realize the full potential of the WISE mission as a roadmap to future exoplanet discoveries. It will yield contamination rates that will be crucial for interpreting all disk searches done with WISE. Our search will yield ~2000 well-vetted nearby disks, including ~60 that the Gaia mission will likely find to contain giant planets. This crucial follow-up work should be done now to take full advantage of Gaia during JWST's planned lifetime.

Michael Line/University of California Santa Cruz

Testing Atmospheric Retrieval Modeling Assumptions for Transiting Planet Atmospheres: Preparatory science for the James Webb Space Telescope and beyond.

The field of transiting exoplanet atmosphere characterization has grown considerably over the past decade given the wealth of photometric and spectroscopic data from the Hubble and Spitzer space telescopes. In order to interpret these data, atmospheric models combined with Bayesian approaches are required. From spectra, these approaches permit us to infer fundamental atmospheric properties and how their compositions can relate back to planet formation. However, such approaches must make a wide range of assumptions regarding the physics/parameterizations included in the model atmospheres. There has yet to be a comprehensive investigation exploring how these model assumptions influence our interpretations of exoplanetary spectra. Understanding the impact of these assumptions is especially important since the James Webb Space Telescope (JWST) is expected to invest a substantial portion of its time observing transiting planet atmospheres. It is therefore prudent to optimize and enhance our tools to maximize the scientific return from the revolutionary data to come. The primary goal of the proposed work is to determine the pieces of information we can robustly learn from transiting planet spectra as obtained by JWST and other future, space-based platforms, by investigating commonly overlooked model assumptions. We propose to explore the following effects and how they impact our ability to infer exoplanet atmospheric properties:

1. Stellar/Planetary Uncertainties: Transit/occultation eclipse depths and subsequent planetary spectra are measured relative to their host stars. How do stellar uncertainties, on radius, effective temperature, metallicity, and gravity, as well as uncertainties in the planetary radius and gravity, propagate into the uncertainties on atmospheric composition and thermal structure? Will these uncertainties significantly bias our atmospheric interpretations? Is it possible to use the relative measurements of the planetary spectra to provide additional constraints on the stellar properties?

2. The “1D” Assumption: Atmospheres are inherently three-dimensional. Many exoplanet atmosphere models, especially within retrieval frameworks, assume 1D physics and chemistry when interpreting spectra. How does this “1D” atmosphere assumption bias our interpretation of exoplanet spectra? Do we have to consider global temperature variations such as day-night contrasts or hot spots? What about spatially inhomogeneous molecular abundances and clouds? How will this change our interpretations of phase resolved spectra?

3. Clouds/Hazes: Understanding how clouds/hazes impact transit spectra is absolutely critical if we are to obtain proper estimates of basic atmospheric quantities. How do the assumptions in cloud physics bias our inferences of molecular abundances in transmission? What kind of data (wavelengths, signal-to-noise, resolution) do we need to infer cloud composition, vertical extent, spatial distribution (patchy or global), and size distributions?

The proposed work is relevant and timely to the scope of the NASA Exoplanet Research program. The proposed work aims to further develop the critical theoretical modeling tools required to rigorously interpret transiting exoplanet atmosphere data in order to maximize the science return from JWST and beyond. This work will serve as a benchmark study for defining the data (wavelength ranges, signal-to-noises, and resolutions) required from a modeling perspective 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". Doing so will allow us to better "understand the chemical and physical processes of exoplanets (their atmospheres)" which will ultimately " improve understanding of the origins of exoplanetary systems" through robust planetary elemental abundance determinations.

Mercedes Lopez-Morales/SAO

Measuring the Masses of K2 Planets with HARPS-N to Determine the Conditions Under Which Planets Retain, or Lose, their Primordial Envelopes

One of the main findings of NASA's Kepler Mission has been an abundance of planets with radii between that of Neptune and Earth around solar type stars, the so-called mini-Neptunes and super-Earths. There is no equivalent of those planets in our Solar System, but about 80 percent of the candidates in the Kepler catalog are in this size range. Therefore, they appear to be the most common type of planets around solar type stars. In spite of their large numbers, we still know very little about the masses of mini-Neptunes and super-Earths, and their densities. There has been some recent progress on this topic, for e.g. as part of an ongoing XRP proposal (14-XRP14_20071; P.I. Charbonneau), our team has measured precise masses for 8 planets with radii between 1 and 2.5 Earths with HARPS-N, and found that all planets smaller than 1.6 Earth radii have core masses consistent with Earth's, while all planets larger than 1.6 Earth radii have H/He envelopes. The current hypothesis is that this is an insolation effect, since all the rocky planets with precise mass measurements are in very short orbits. However, that hypothesis has not been fully tested, and many other questions about the formation and evolution of these small planets remain unsolved, i.e. what is the rocky/non-rocky ratio of these planets? Are the observed rocky planets evaporated cores of sub-Neptunes, or did they form as bare cores? Can very short period planets retain a significant envelope? Is the currently hypothesized non-rocky/rocky transition at 1.5-1.7 Earth radii real?

Precision radial velocity mass measurements so far suffer from an observational bias, in which larger radius planets with small radial velocity signals have been overlooked. These cases would form a population of very low-mass, gaseous planets, which 1) disagree with the current conclusion that all low mass planets below 6 Earth masses are rocky, 2) serve to test current formation/gas accretion and evaporation models, and 3) have large, extended, easier to study atmospheres.

In this project we propose to measure the masses of at least 10 planets with radii smaller than 4 Earth radii and spanning a range of insolation levels, to precisions of at least 20 percent. Our team has done extensive work producing catalogs of K2 planet candidates and stellar characterization spectra. From that work, we are selecting targets for this project that best match the criteria to test the questions listed above. We focus on K2 targets, since this mission is producing candidates around bright stars, which are better suited than the original Kepler planets to become prime targets for precise radial velocity measurements and future atmospheric follow-up.

The masses of those planets will be measured with HARPS-N, a high-resolution spectrograph optimized for highly precise radial velocity measurements. HARPS-N was specifically built to follow-up Kepler planets, and planets found by later missions, such as K2 and TESS. We have 80 nights per year of guaranteed time dedicated to this project, and in the past three years, our team has published precise masses for several planets in that radius regime.

We expect the results of this work will increase the scientific impact of the NASA Kepler Mission by measuring masses for the most interesting targets discovered by K2. Our results will also improve our understanding of the origins and evolution of exoplanetary systems and will help identify suitable small planets around relatively bright stars, for detailed atmospheric characterization with HST and JWST.

Roxana Lupu/Bay Area Environmental Research Institute
Model Atmospheres and Transit Spectra for Hot Rocky Planets

We propose to build a versatile set of self-consistent atmospheric models for hot rocky exoplanets and use them to predict their transit and eclipse spectra. Hot rocky exoplanets will form the majority of small planets in close-in orbits to be discovered by the TESS and Kepler K2 missions, and offer the best opportunity for characterization with current and future instruments. We will use fully non-grey radiative-convective atmospheric structure codes with cloud formation and vertical mixing, combined with a self-consistent treatment of gas chemistry above the magma ocean. Being in equilibrium with the surface, the vaporized rock material can be a good tracer of the bulk composition of the planet. We will derive the atmospheric structure and escape rates considering both volatile-free and volatile bearing compositions, which reflect the diversity of hot rocky planet atmospheres. Our models will inform follow- up observations with JWST and ground-based instruments, aid the interpretation of transit and eclipse spectra, and provide a better understanding of volatile loss in these atmospheres. Such results will help refine our picture of rocky planet formation and evolution.

Planets in ultra-short period (USP) orbits are a special class of hot rocky exoplanets. As shown by Kepler, these planets are generally smaller than 2 Earth radii, suggesting that they are likely to be rocky and could have lost their volatiles through photo-evaporation. Being close to their host stars, these planets are ultra-hot, with estimated temperatures of 1000-3000 K. A number of USP planets have been already discovered (e.g. Kepler-78 b,

CoRoT-7 b, Kepler-10 b), and this number is expected to grow by confirming additional planet candidates. The characterization of planets on ultra-short orbits is advantageous due to the larger number of observable transits, and the larger transit signal in the case of an evaporating atmosphere. Much advance has been made in understanding and characterizing hot Jupiters in similar transit configurations. For example, Na has been the first species to be detected in an exoplanet atmosphere, by observing the evaporating hot-Jupiter HD209458b. Understanding the interplay between the magma outgassing and volatile loss will be an important part of this project.

Our team has the expertise in the chemistry, radiative transfer, and atmospheric escape modeling at these exotic temperatures. Our recent work has analyzed the emerging atmospheres of terrestrial planets after giant impacts, using a well-established radiative-convective atmospheric structure code, with an extensive opacity database for all relevant molecules, and the chemistry self-consistently calculated for continental crust and bulk silicate earth compositions. We will expand on this work by considering a wider range of chemical compositions, assessing the importance of clouds and generating cloudy models, and developing dis-equilibrium models by taking into account vertical mixing and photochemistry. Photo-evaporation will be considered in the energy balance between heating, cooling and mass loss. We also have in-house codes to generate high-resolution eclipse spectra and predict transit depths and observable signatures.

The development of the atmospheric code, the molecular opacity updates, the atmospheric structure calculations and the high resolution eclipse spectra will be performed by R. Lupu, M. Marley, and R. Freedman at NASA Ames. The atmospheric chemistry grids will be provided by B. Fegley and K. Lodders at Washington University. The transit spectra and observational features will be computed by J. Fortney at UCSC, and the atmospheric escape calculations will be performed by K. Zahnle at NASA Ames. This proposal addresses the following goals of the Exoplanet Research program: explain observations of exoplanetary systems, and understand the chemical and physical processes of exoplanets. Our results will also inform future JWST observations.

Wladimir Lyra/California State University Northridge
Origin of hot Super-Earths and the vortex-assisted mode of planet formation.

In spite of steady advances, planet formation remains, by and large, a mystery. Although a relatively consistent theory has been developed in the past two decades, its application to the observed distribution of exoplanets has not fared too well. If the statistics of discovered exoplanets suggest that planets form efficiently, there are still fundamental unsolved problems, such as excessive inward drift of grains in protoplanetary disks during planet formation. State-of-the-art theories invoke dust traps to overcome this problem, and recent high-resolution observations of protoplanetary disks show a high-contrast crescent-shaped emission on one side of the star, originating from millimeter-sized grains. The favored hypothesis borrows from the planet formation literature by suggesting that this asymmetry is the result of dust trapping in giant anticyclonic vortices. This idea, however, is not without problems. Vortices have been extensively studied, and

some of their understood properties conflict with them being the culprit of the observed asymmetries. Understanding these conflicts will provide constraints for the theory and advance our interpretation of the observations. In this proposal, we aim to show that vortex trapping is a viable mechanism for planet formation. This is possible because 1) large-scale vortices are expected at turbulent/quiescent transitions in the disk 2) vortices are expected in the laminar zones 3) vortices should be excellent traps for grains and thus planet formation sites; 4) grain drift from outer radii brings more planet building blocks to the vortex; and 5) The turbulent/laminar zone boundary is also a migration stopping point. We propose a set of hydrodynamical simulations including embedded solid particles to decisively demonstrate the efficiency of vortex-assisted planet formation.

Bruce Macintosh/Stanford University
The Gemini Planet Imager Exoplanet Survey: Completion and Analysis

The Gemini Planet Imager (GPI) is an advanced ground-based coronagraphic instrument deployed on the Gemini South Telescope. GPI is capable of detecting young (<300 Myr) giant (>1 MJ) planets through near-infrared emission, spectroscopically characterizing their atmospheres, and constraining their orbital properties. In late 2014 we began using GPI for a large-scale search for such planets, the Gemini Planet Imager Exoplanet Survey (GPIES). From 2015-2018 GPIES will observe 600 nearby young stars. To date, the survey has discovered the cool, methane-dominated planet 51 Eridani b, characterized previously-known planets, mapped circumstellar debris disks, and detected several brown dwarf companions, as well as detecting a large number of candidate exoplanets. Detected companions tentatively show evidence of a planetary semi-major-axis distribution that is rising as we approach the ice line.

We propose to complete the GPIES campaign observations of new stars and follow up candidate companions to determine their true nature. We will develop Bayseian algorithms to properly characterize the completeness and sensitivity of the survey. Using these, we will assess the statistical properties of the population of wide orbit (>5 AU) giant planets. In comparison with Doppler-detected planet populations we will determine if we have indeed reached the outer edge of traditional planet formation, or if wide-orbit giant planets are formed by a different process than their close-in counterparts. We will also analyze the statistical association of giant planets with stellar spectral type and with the presence of a circumstellar debris disk.

Rebecca Martin/University of Nevada, Las Vegas
Planet Formation in Binary Star Systems

About half of observed exoplanets are estimated to be in binary systems. Understanding planet formation and evolution in binaries is therefore essential for explaining observed exoplanet properties. Recently, we discovered that a highly misaligned circumstellar disk in a binary system can undergo global Kozai-Lidov (KL) oscillations of the disk inclination and eccentricity. These oscillations likely have a significant impact on the

formation and orbital evolution of planets in binary star systems. Planet formation by core accretion cannot operate during KL oscillations of the disk. First, we propose to consider the process of disk mass transfer between the binary members. Secondly, we will investigate the possibility of planet formation by disk fragmentation. Disk self gravity can weaken or suppress the oscillations during the early disk evolution when the disk mass is relatively high for a narrow range of parameters. Thirdly, we will investigate the evolution of a planet whose orbit is initially aligned with respect to the disk, but misaligned with respect to the orbit of the binary. We will study how these processes relate to observations of star-spin and planet orbit misalignment and to observations of planets that appear to be undergoing KL oscillations. Finally, we will analyze the evolution of misaligned multi-planet systems. This theoretical work will involve a combination of analytic and numerical techniques. The aim of this research is to shed some light on the formation of planets in binary star systems and to contribute to NASA's goal of understanding of the origins of exoplanetary systems.

David Nesvorny/Southwest Research Institute
Studies of the Origin of Compact Planetary Systems

The majority of planets discovered by the Kepler telescope are super-Earth and mini-Neptunes in close-in multiplanet systems. The orbits are often closely packed together, typically non-resonant, and expected to be nearly circular and nearly co-planar. The prevalence of these systems in the Kepler dataset suggests that they may represent the main channel of planetary formation in the Galaxy. It is unsettling that we do not know how these planetary systems form. This is one of the most fundamental unanswered questions in planetary science.

Here we propose to study several formation models, including a new model in which planets efficiently form by accretion of small bodies (pebbles, boulders) drifting to the inner parts of the protoplanetary disk by aerodynamic gas drag. Our main goal is to understand the dynamics of growing protoplanets as they gravitationally interact among themselves and with the gas disk. The research will be conducted with a numerical code, FargoSyMBA, that we developed to this purpose. The new code is based on the hydrodynamical code known as Fargo, which we interfaced with an efficient N-body integrator known as SyMBA.

The specific result that we will obtain in the work proposed here is how the number, masses and orbits of planets in the assembled systems depend on model parameters, and how these properties compare with observations. The general impact of the proposed work will be significant in that it will help us to better understand how planetary systems form, and what is the role of migration in their assembly. This is one of the central research themes in planetary science.

Relevance to NASA Strategic Goals and the Exoplanets Research Program

The proposed research is fundamental to understanding the formation and early evolution of exoplanetary systems. This is a central theme of NASA's Strategic Goals and the Exoplanets Research program. Specifically, the NRA for the Exoplanets Research program states that the program "solicits basic research proposals to conduct scientific investigations related to the research of extrasolar planets", and that the program objectives include "improving understanding of the origins of exoplanetary systems". The types of studies that are supported include the "theoretical studies". Here we propose theoretical investigations of the formation and early dynamical evolution of compact (close-in and tightly packed) exoplanetary systems.

This theme is directly relev ant to the NASA Strategic Goals and Research Objectives, and to the Exoplanets Research program in particular. Our goal is to study the dynamical evolution of planetary systems and constrain exoplanetary formation processes. The proposed work will make use of the data acquired by NASA's Kepler spacecraft, which are publicly available at the Mikulski Archive for Space Telescopes (MAST).

Marc Neveu/Arizona State University
No One's Home: the Fate of Carbon on Lifeless Earths

Although several thousands of exoplanets are now known, including many terrestrial planets, their possible geology and climates remain poorly understood and understudied. Yet, understanding how elements such as carbon are cycled between a planet's interior, surface, and atmosphere is crucial to predict how lifeless planets operate and, by contrast, be able to detect deviations from abiotic backgrounds due to biology, the holy grail of exoplanet science. As a first, feasible step towards the difficult, long-term goal of understanding how key reactive elements (H, C, N, O, S) are cycled in the atmospheres, surfaces, and interiors of terrestrial exoplanets through time, we propose to carry out a self-consistent theoretical study of the fate of carbon in the atmospheres and at the surfaces of Earth-like, lifeless exoplanets. We will:

1. Model the near-surface geochemistry and geophysics of the carbon cycle to determine net carbon gas fluxes as a function of terrestrial planet size and redox conditions;
2. Model the atmospheric fate of carbon species as a function of stellar input;
3. Perform simulations that self-consistently combine geological and atmospheric processes;
4. Convert resulting atmospheric compositions to spectra to be archived as a public database for use by observers.

We will track the abiotic fate of carbon and its atmospheric expression on Earth-like planets as a function of three key parameters: planet size, surface and atmospheric redox conditions, and stellar irradiation. To do so, we will further develop and use state-of-the-art planetary geological ("Geo") and atmospheric ("Atmos") models.

We have previously developed a code that couples geophysical evolution and water-rock geochemistry (Neveu et al. 2015, GRL 42, 10197). Using this code, we will calculate the

speciation of carbon species versus depth in subaerial oceans, their possible incorporation into the crust by water-rock interaction at the seafloor or by subduction of sediments, and outgassing as a function of temperature, pressure, and fluid/rock composition. We will expand this code with benchmarked parameterizations of land and seafloor weathering and outgassing rates. This modeling will result in detailed boundary conditions to be implemented into an existing atmospheric photochemical-climate model (Domagal-Goldman et al. 2014, ApJ 792, 90).

The atmospheric model will be used to predict species mixing ratios from net surface fluxes, given planetary and stellar parameters. The models will be benchmarked against what is known of the surfaces and atmospheres of the Earth (present and prior to atmospheric oxygenation) and Titan.
Atmospheric model outputs will be fed back into the geological model in combined simulations of carbon cycling. We will investigate in detail the mutual feedbacks between geological and atmospheric processes, so far understudied for terrestrial exoplanets. The resulting atmospheric compositions will be converted to predicted exoplanet spectra using the Spectral Mapping Atmospheric Radiative Transfer model (SMART; Meadows & Crisp 1996, JGR 101, 4595). This grid of spectra will be made freely available to the exoplanet community.

This proposal is relevant to the Exoplanets Research Program (E.3) objectives, as it "supports directly the scientific goals of advancing our knowledge and understanding of exoplanetary systems." It involves the "characterization of exoplanets (including their surfaces, interiors, and atmospheres) […] including the determination of their compositions, dynamics, energetics, and chemical behaviors." This investigation will also advance "understanding the chemical and physical processes of exoplanets (including the state and evolution of their surfaces, interiors, and atmospheres)."

Furthermore, this proposal is not "aimed at investigating the habitability of an exoplanet" and therefore not relevant to the Habitable Worlds program element (E.4).

Klaus Pontoppidan/Space Telescope Science Institute
Retrieving the Molecular Composition of Planet-Forming Material: An Accurate Non-LTE Radiative Transfer Code for JWST

Based on the observed distributions of exoplanets and dynamical models of their evolution, the primary planet-forming regions of protoplanetary disks are thought to span distances of 1-20 AU from typical stars. A key observational challenge of the next decade will be to understand the links between the formation of planets in protoplanetary disks and the chemical composition of exoplanets. Potentially habitable planets in particular are likely formed by solids growing within radii of a few AU, augmented by unknown contributions from volatiles formed at larger radii of 10-50 AU. The basic chemical composition of these inner disk regions is characterized by near- to far-infrared (2-200 micron) emission lines from molecular gas at temperatures of 50-1500 K. A critical step toward measuring the chemical composition of planet-forming regions is therefore to

convert observed infrared molecular line fluxes, profiles and images to gas temperatures, densities and molecular abundances. However, current techniques typically employ approximate radiative transfer methods and assumptions of local thermodynamic equilibrium (LTE) to retrieve abundances, leading to uncertainties of orders of magnitude and inconclusive comparisons to chemical models. Ultimately, the scientific impact of the high quality spectroscopic data expected from the James Webb Space Telescope (JWST) will be limited by the availability of radiative transfer tools for infrared molecular lines.

We propose to develop a numerically accurate, non-LTE 3D line radiative transfer code, needed to interpret mid-infrared molecular line observations of protoplanetary and debris disks in preparation for the James Webb Space Telescope (JWST). This will be accomplished by adding critical functionality to the existing Monte Carlo code LIME, which was originally developed to support (sub)millimeter interferometric observations. In contrast to existing infrared codes, LIME calculates the exact statistical balance of arbitrary collections of molecular lines, and does not use large velocity gradient (LVG) or escape probability approximations. However, to use LIME for infrared line radiative transfer, new functionality must be added and tested, such as dust scattering, UV fluorescence, and interfaces with public state-of-the art 3D dust radiative transfer codes (e.g., RADMC3D) and thermo-chemical codes (e.g, ProDiMo).

Infrared transitions of molecules expected to be ubiquitous in JWST spectra currently do not have good databases applicable to astrophysical modeling and protoplanetary disks, including water, OH, CO2, NH3, CH4, HCN, etc. Obtaining accurate solutions of the non-LTE line transfer problem in 3D in the infrared is computationally intensive. We propose to benchmark the new code relative to existing, approximate methods to determine whether they are accurate, and under what conditions. We will also create conversion tables between mid-infrared line strengths of water, OH, CH4, NH3, CH3OH, CO2 and other species expected to be observed with JWST, and their relative abundances in planet-forming regions. We propose to apply the new IR-LIME to retrieve molecular abundances from archival and new spectroscopic observations with Spitzer/Herschel/Keck/VLT of CO, water, OH and organic molecules, and to publish comprehensive tables of retrieved molecular abundances in protoplanetary disks.

The proposed research is relevant to the XRP call, since it addresses a critical step in inferring the chemical abundances of planet-forming material, which in turn can be compared to the observed compositions of exoplanets, thereby improving our understanding of the origins of exoplanetary systems. The proposed research is particularly timely as the first JWST science data are expected to become available toward the end of the three-year duration of the project.

Tamara Rogers/Planetary Science Institute
The Role of Wave Dynamics on the Origin and Evolution of Hot Jupiters

We propose to study the role of wave dynamics on the origin and evolution of hot Jupiters. This work will address how angular momentum transport by tidally and convectively driven waves affects the orbital evolution and observational inferences of hot Jupiters. We will use two (2D) and three (3D) dimensional nonlinear, hydrodynamic simulations to understand: 1) angular momentum transport by convectively driven waves within stars and how these waves affect stellar rotational evolution, 2) the interaction of tidally-induced waves with convectively-generated waves and how their mutual dissipation affects the orbital evolution of hot Jupiters, and 3) how this combined angular momentum transport affects the observational inferences of the evolution of planetary orbital properties. Specifically, these studies will shed light on the observed dichotomy between the obliquity of planets around hot stars versus those around cool stars and will provide an estimate for the tidal dissipation function, Q, for exoplanets' host stars. In order to test our models we will make observational predictions which may be checked with existing data from NASA's Kepler mission and forthcoming searches from the TESS mission as well as ground-based follow-up radial velocity observations.

Verne Smith/National Optical Astronomy Observatory
It's Elementary: Chemical Compositions and Characterization of Exoplanet-hosting M-dwarfs using APOGEE

Science Goals and Objectives: The determination of accurate physical parameters for stars which host exoplanets is a crucial step in characterizing the size and nature of the planets themselves; one can only know the planet to the level that the host star is known. This program will carry out a detailed spectral analysis for samples of both field M-dwarf stars, along with planet-hosting M-dwarfs uncovered by the Kepler mission, and in particular those hosting multiple small planets (either Earth-size or "super-Earth" size). High-resolution near-infrared spectra will be analyzed using new model atmospheres and analysis techniques pioneered here. The focus of this proposal is both to derive accurate stellar parameters and metallicities, as well pioneer the study of detailed quantitative chemical analyses of 15 key elements in cool M-dwarfs that cannot be obtained from optical spectroscopy. The Kepler mission M-dwarfs are an important component in both transit and radial-velocity searches for exoplanets, thanks to the enhanced detectability of small planets due to the low stellar masses of M-dwarfs, their low luminosities, and small stellar radii. In addition, M-dwarfs are the most numerous stars in the Galaxy. As the extended Kepler mission (K2) uncovers new M-dwarf planet-hosting stars, this project will continue to target strategic subsets of newly identified exoplanet-hosting M-dwarfs in future years.

Methodology: Our group has developed accurate and efficient techniques for chemically analyzing cool red giants in the near-infrared H-band (e.g., Smith et al. 2013, ApJ, 765, 16; Cunha et al. 2015, ApJL, 798, 41) as a result of our participation in the SDSS III APOGEE and SDSS IV APOGEE-2 (Apache Point Observatory Galactic Evolution

Experiment) Surveys. We are currently conducting an Ancillary Science Program for APOGEE-2 to target all exoplanet-hosting M-dwarfs in the Kepler field and will develop the techniques necessary to use the APOGEE analysis tools to include M-dwarfs in an effective and efficient manner. As additional Extended Kepler Mission (K2) M-dwarf hosts are uncovered, we will target these in the future (APOGEE-2 runs through 2020).

Relevance to Exoplanet Research: The proposers here have the expertise in stellar abundance analysis and are well positioned to provide the first high-resolution NIR spectroscopic stellar parameter and abundance analyses of confirmed Kepler M-dwarf small-planet systems. Possible connections between host-star characteristics, such as mass or chemical composition, and the underlying nature of daughter planetary systems, such as masses or even orbital architectures, will be extended to the regime of the M-dwarfs. Low-resolution spectroscopic analyses of M-dwarfs can provide overall estimates of stellar parameters, but these cannot provide the detailed chemical abundance signatures which can be analyzed in high-resolution APOGEE spectra, such as individual C, N, O, Na, Mg, Al, Si, S, K, Ca, Ti, Mn, Fe, or Ni abundances, some of which play fundamental roles in planet formation. This project opens a new window into a major class of stars, whose significance as planet hosts will play an increasingly important role in the future, such as representing a large fraction of targets for the TESS mission.

Geronimo Villanueva/NASA - Goddard Space Flight Center

Modeling of Non-Equilibrated Emission from Exoplanets for a Broad Range of Temperatures, Host Stars and Molecules (H2O, CH4, CO2, CO, NH3, HCN)

Non-LTE emission can be much greater than the intrinsic planetary emission due to stellar flux amplifications via fluorescence cascades, and it may provide a new means to characterize the composition of exoplanets. Are we properly interpreting exoplanet spectra using current emission models? Can molecular signatures be detected in these intriguing newly discovered hazy exoplanets? Non-equilibrated (non-LTE) emission may hold the answer. We propose to model non-equilibrated emission in exoplanets for several key species (H2O, CH4, CO2, CO, NH3 and HCN), incorporating comprehensive high-energy databases (containing billions of spectral lines), realistic climate models, and advanced radiative transfer models.

Specifically, we propose the following tasks:

- Compile a set of density and temperature profiles for exoplanets at different distances from the host-star, radius and density by making use of our 1D coupled climate-photochemistry model.
- Compile a realistic set of high-resolution stellar spectra covering a broad range of host stars by combining theoretical and astronomical data.
- Develop high-energy and self-consistent linelists for CH4, CO and CO2 applicable to high-resolution spectra, building on our work for H2O, NH3 and HCN.
- Compute non-LTE branching rates, cascades and probabilities for the 80 exoplanetary cases, making use of our General Fluorescence Model (GFM).

- Synthesize non-LTE spectra by integrating the computed cascade probabilities, and LTE fluxes for the equilibrated regions of the atmosphere, leading to 80 high-resolution templates for 6 molecules.
- Compare the templates to the known exoplanet population to predict which planets would be the best candidates for detection of non-LTE emission using current and near-term observational resources (HST, Keck/VLT, JWST, WFIRST and ELT).

This proposal is highly consistent with the goals of the ROSES Exoplanets Research Program, in that the proposed non-LTE modeling directly supports the goal of understanding exoplanetary systems by aiding in the detection of molecular signatures of exoplanets; helping to explain current and future observations of exoplanetary systems; and by constraining the chemical and physical processes active in exoplanets.

Alycia Weinberger/Carnegie Institution of Washington
Developing Insights into Debris Disk Composition from Dust Scattering

Science Goals: To enable interpretation of visible to near-IR spectrophotometric imaging of debris disks, we propose realistic modeling of scattering of light by small aggregate dust grains and new laboratory measurements of meteoritic organic analogs. We will determine if disk colors, phase functions, and polarizations place unique constraints on the composition of debris dust. Ongoing collisions of planetesimals generate dust; therefore, the dust provides unique information on compositions of the parent bodies. These exosolar analogs of asteroids and comets bear clues to the history of a planetary system including migration and thermal processing. In the solar system, small bodies delivered volatiles to Earth, and they presumably play the same role for exoplanets.

Because directly imaged debris disks are cold, they have no solid-state emission features. Grain scattering properties as a function of wavelength are our only tool to reveal their compositions. Hubble Space Telescope (HST) imaging showed debris disks to be populated with small grains, a few tenths of a micron and larger. Radiation pressure and blasting by the interstellar medium sweep the dust away. New work from HST and ground-based adaptive optics systems reveal the color and polarization of the scattered light at wavelengths from visible to near-IR, with two dozen disks imaged at some subset of wavelengths. Far-IR and submm images from Herschel and ALMA show that the same disks also contain large, i.e. mm-sized, grains. Our goal is to develop dust calculations so that spectrophotometry of disks can determine dust compositions.

Solar system interplanetary dust particles are fluffy aggregates, but most previous work on debris disk composition relied on Mie theory, i.e. assumed compact spherical grains. Mie calculations do not reproduce the observed colors and phase functions observed from debris disks. The few more complex calculations that exist do not explore the range of compositions and sizes relevant to debris disk dust. In particular, we expect grains to be mixtures of silicates with ice and carbonaceous inclusions and to have porosities that reflect either cometary-like (high volatile content) or asteroidal-like (compacted) structures.

Methodology: We propose to make discrete dipole (DDA) calculations of the interaction of light with debris-disk-like particles. DDA does a better job modeling high porosity than other approximations such as effective medium theory and provides the efficiencies of both scattering and absorption. We will calculate grain scattering efficiencies, albedos, phase functions, and polarizations for wavelengths out to a few microns for grains in which we vary total size and composition. Into a range of grain shapes and sizes, we will incorporate silicates (amorphous and crystalline), carbonaceous components (organics and amorphous), ices, and porosities. To expand the library of carbonaceous components, we will measure UV to near-infrared absorption spectra of laboratory-generated analogs to primitive solar system organic solids. We will compare the resulting grid of calculations to the colors of disks to determine how precisely dust composition may be estimated with spatially resolved photometry and spectroscopy.

Relevance: Debris disks are the relics of formation and evolution of planetary systems, and they connect our solar system's small body population with that of exosolar systems. The can “improve our understanding of the origins of exoplanetary systems”. We are currently using HST and ground-based adaptive optics systems to image disks from 0.4 - 4 microns. We will compare our new scattering calculations to existing data, and future missions that will add new disk color images, such as JWST and a WFIRST-AFTA coronagraph, provide a further impetus to make such calculations.

John Wisniewski/University of Oklahoma
Exploring the Final Stages of Giant Planet Formation

Transitional disks are an intermediate stage between gas-rich protoplanetary disks and older debris disks/young planetary systems. They have attracted recent interest as high resolution, high contrast imaging facilities have begun to resolve indirect and direct signatures of recently formed planetary bodies in these systems across a broad range of wavelengths (near-IR, mid-IR, mm). Regions in disks where we expect giant planets to have recently formed can be identified by comparison of sub-mm imagery with NIR high contrast imagery. Planets have recently been directly imaged in a few systems. If the transitional disk phase is a typical step in clearing of disks, and most of these have structure consistent with disk-planet interactions, giant planets should be relatively common.

Imaging surveys of nearby moving groups find a ~2% overall giant planet frequency in the 5-150 AU range. However, the frequency of giant planets on wide orbits might be significantly higher in systems with circumstellar disks, and there could be significant differences in frequency with host star and disk properties. For example, among the 8 beta Pictoris moving group A - early F stars, 2 planets are already known, while 2 other systems host transiting exocomets similar to those seen in spectra of beta Pic and used to predict the existence of beta Pictoris b. These findings suggest that the giant planet detection rate is >25% and may reach 50%. Moreover, previous exoplanet surveys could reach only bodies with masses >5 MJup in transitional disks and at inner working angles

(IWA) > 0.15" (21 AU at 140 pc). A new era of high contrast imaging has begun with extreme adaptive optics and advanced coronagraphs that achieve 3x smaller IWAs and an order of magnitude higher contrasts with respect to their host stars. We can now probe the giant exoplanet frequency distribution in forming planetary systems on scales comparable to our outer solar system.

We propose to build up the SEEDS survey and conduct a 3 part study to:

1) Locate likely regions of recent planet formation in transitional disks;
2) Conduct an imaging search for planets in these transitional disks with evidence of recent planet formation;
3) Conduct an imaging planet search for planets in young, WISE-selected debris disks

We will utilize extreme AO NIR imagery both from Subaru and Gemini, as well as high-resolution mm imagery from ALMA. Our survey will allow us to identify planets in transitional disks which are still accreting material, and to test whether young debris disk planets have a similar spatial distribution to those seen in transitional disks, implying in situ formation at large distances from their host stars. Our investigation leverages a strong existing international set of collaborators, the largest extant high-contrast imaging study of transitional disks (i.e SEEDS), and significant amount of approved observing time (Subaru, Gemini, ALMA, SMA). This work is directly applicable to the goals of the Exoplanet Research Program and specifically the objective of detection and characterization of planets and planetary systems outside of our Solar System.