Exoplanets Research Program
Abstracts of Selected Proposals
NNH20ZDA001N-XRP

Below are the abstracts of the proposals selected for funding for the 2020 Exoplanets Research Program (XRP). Principal Investigator (PI) name, institution, and proposal title are also included. Of the 153 proposals that were received in response to this opportunity, 26 were selected for funding on October 23, 2020.

Eric Agol / University Of Washington, Seattle
Probing the compositions of multi-planet transiting systems with photodynamics

Transiting planets from the Kepler, K2, and TESS missions present an opportunity to measure the radii of very small planets, approaching the size of the Earth (and even smaller). However, for the majority of these systems we cannot measure the masses of these planets from radial velocity: either the stars are too faint and/or the radial velocity amplitudes too small. So the question remains: what are small planets made of? Mostly rock and iron? If so, how much of each? Or a gaseous envelope as well?

Here we propose to improve the constraints upon the compositions of transiting exoplanets with photodynamical characterization of multi-planet systems. We will take a two-pronged approach to this problem: a). better characterizing planet radii in multi-planet systems to refine the radius valley measurements; b). measuring planet masses from transit-timing in a subset of these systems.

The distribution of planet sizes at short orbital periods has a minimum near ~1.8 times the radius of Earth, referred to as the "radius valley" or "Fulton gap." This gap has been attributed to multiple possible origins, while each of these models makes predictions for the dependence of the gap on the planet, orbital, and stellar properties. However, distinguishing between these models is currently limited by i). the precision of the measurements of planetary radii, and ii). the small size of the sample of planets with high-precision measurements.

We propose to develop a path towards refining planetary radius measurements for a significant number of transiting multi-planet systems in the Kepler, K2 and TESS datasets. There are two barriers to measuring planetary radii with high precision from transiting planet data: uncertainties on the planet-star radius-ratios, thanks to degeneracy with impact parameter and limb-darkening, and uncertainties on the stellar radius measurements. Multi-planet systems offer the prospects for addressing these limitations with better characterization of both the planets and the star. Our tool will be a photodynamical model, which combine photometry and dynamics to model the entire transit light curve simultaneously. A joint analysis of the planets will solve both problems: it will break the degeneracy between planet radius and impact parameter, and it will provide a more precise estimate of the stellar density. Together with luminosity/temperature estimates from GAIA, this will provide precise characterization of the planetary radii.

We will leverage tools we have been developing over the last few years to create a fully differentiable photodynamic model accounting for correlated noise. We will then use a Hamiltonian Monte Carlo approach to increase the efficiency of sampling these high-dimensional systems. We have demonstrated this capability with the TRAPPIST-1 system, in which case the stellar density is determined with a precision of ~2%, while the planetary radii are determined with a precision of 1-2%. We plan to apply a similar methodology to the Kepler, K2 and TESS multi-planet systems for which there are 10^3 planets with periods < 100 days which straddle the radius valley.

In a small number of cases we can measure masses of the transiting exoplanets from photodynamics based upon transit-timing variations (TTVs). We will help to refine the mass-radius relation of small exoplanets with our analysis, constraining their bulk densities, which provides constraints on the compositions which complement to the radius valley measurements.

In sum, we will develop a sample of order 10^3 planets with precisely measured radii to constrain the radius valley to higher precision than is currently possible. For a sub-sample, of order 10^2 planets, we will measure masses with TTVs, yielding constraints on the planets' densities and compositions. Together these results will be the ability to better test models for the origin of the valley, and the compositions of small exoplanets.

Travis Barman / University Of Arizona
What do exoplanets endure? Predicting the full spectral irradiance of all exoplanetary systems.

The characterization of exoplanets, either theoretically or observationally depends heavily on our understanding of host star properties. This dependence is particularly apparent when modeling the atmospheres of exoplanets where the stellar irradiation is the dominant source of energy. There are many well known examples where the stellar radiation is an important regulator of the planet s atmospheric temperature-pressure profile, dynamics, chemistry, and longterm cooling evolution. Consequently, the first but often under appreciated step when modeling an exoplanet atmosphere is obtaining a model spectrum of the host star. The true stellar fluxes as seen by the planet, however, are often considerably more complex than represented by a synthetic spectrum calculated using a standard one-dimensional photosphere-only model assumed to be in local thermodynamic equilibrium (LTE). Spatial variations due to star spots, sudden increases in high-energy fluxes from flares, and the X-ray to UV (XUV) fluxes generated in the chromospheres, transition regions and coronae are all absent from the majority of stellar models used to study exoplanets.

There is growing appreciation for the importance of the XUV and its influence on a range of planets including ultra-hot Jupiters and potentially habitable worlds. For example, while late-type dwarfs (e.g., K through M) emit the majority of their radiation at optical to near-infrared wavelengths, the small fraction that emerges across the XUV can drive significant atmosphere escape or influence the interpretation of biosignatures. Furthermore, as observations begin to probe exoplanet atmospheres at higher spectral resolution, a detailed understanding of the stellar spectrum at comparable resolution is critically important when interpreting transit and secondary eclipse spectra (e.g., to correct for stellar spot contamination).

Observationally, the XUV will remain out of reach for the foreseeable future leaving stellar atmosphere modeling as the only path forward. All existing libraries of synthetic stellar spectra are either missing the XUV or are grossly inadequate because they lack plausible descriptions for the uppermost regions of the stellar atmosphere where the XUV emerges. Furthermore, the bulk of our understanding and ability to model the stellar XUV rely on models engineered for the Sun and a small but growing number of similar models for M dwarfs. We propose to develop new atmosphere models for exoplanet host stars across the entire main sequence that include not only the photosphere but also semi-empirical models for chromospheres, transition regions and coronae (for those stars that require them). Our models will include the state-of-the-art in non-LTE calculations, include the most up-to-date and compete set of atomic and molecular data and provide very high spectral resolution synthetic spectra from the X-ray to the radio. Employing strategies successfully used for the Sun, we will explore the contributions of surface features (e.g., plage, facula, spots) and various levels of activity (including flares) to the full spectral irradiance. We will make available to the community the first comprehensive synthetic spectral library that includes the XUV for all known exoplanet host stars.

Peter Bernath / Old Dominion University Research Foundation
Spectroscopy for Exoplanets

Observations of exoplanet atmospheres are underway in many research groups; however, the interpretation of these observations requires suitable reference spectral data based on laboratory measurements. Most observed exoplanet atmospheres, and those likely to be detected in the near future, are hot. This proposal will focus on the laboratory spectroscopy of molecules of importance in the atmospheres of hot super-Earth and hot Jupiter exoplanets, including TiO, VO, FeH, NaO, LiO, and NaOH. We will deliver spectroscopic line lists or absorption cross sections based on new experimental spectroscopic measurements and ab initio calculations for these molecular species. The measurements will be made with a high resolution Bruker Fourier transform infrared spectrometer (FTS) using high temperature furnace sources. Our data will be useful for the identification of molecules in, and simulation of, exoplanet atmospheric spectra. The Exoplanets Research program announcement states that the NRA supports observational, laboratory, modeling, and theoretical studies that focus on improving our understanding of exoplanetary systems." This proposal is for laboratory studies that will improve the understanding of exoplanet atmospheres relevant to current and future NASA missions. Current NASA missions, such as TESS and HST, are used to study exoplanets. In the future, JWST will result in the characterization of large numbers of exoplanets; WFIRST will also target exoplanets.

Brendan Bowler / University Of Texas, Austin
Transforming Yields of Direct Imaging Planet Searches With Young Accelerating Stars

High-contrast imaging is a powerful tool to probe the atmospheres and orbital architectures of long-period planets. The development of extreme adaptive optics instruments, novel coronagraph designs, and increasingly sophisticated post-processing methods has facilitated the discovery of about a dozen planets with separations within 100 AU via direct imaging. Despite the scientific importance and long-term potential of this planet-finding technique, the scarcity of giant planets at large separations has emerged as the single largest barrier that has limited the scientific growth of this field over the past decade.

The goal of this program is to dramatically improve these outcomes and deliver discoveries of new planets for existing telescopes and future facilities like JWST. Our approach is to identify promising targets based on their astrometric reflex accelerations from Hipparcos and Gaia DR2, which span a 24 year baseline. By focusing on targets with astrometric evidence of long-period planets, this program will facilitate the first significant transition from blind direct imaging surveys to dynamically informed targets, mitigating the impact of low planet occurrence rates at wide separations that have hindered previous campaigns.

Our program consists of three phases: (1) identify young stars with low-amplitude astrometric accelerations, (2) conduct follow up high-resolution imaging and spectroscopy to remove false positives caused by stellar, brown dwarf, and white dwarf companions, and (3) carry out a focused high-contrast imaging survey of the most promising young stars that have accelerations consistent with long-period giant planets. We will make use of the new Hipparcos-Gaia Catalog of Accelerations (HGCA), which is the largest and most sensitive catalog of accelerating nearby bright stars to date. To demonstrate the utility and reliability of the HGCA catalog, our team recently used the astrometric accelerations of host stars with known brown dwarf, white dwarf, and giant planet companions to constrain their orbits and dynamical masses. This strategy has opened an unprecedented opportunity to find young stars with dynamical evidence of low-mass companions at separations accessible to the current generation of high-contrast imagers.

Our program is well-matched with the primary goal of NASA's Exoplanet Research Program to discover and characterize planetary systems. In particular, these observations will be used to identify optimal targets with strategic relevance for follow-up high-contrast near- and mid-infrared imaging using JWST and ground-based facilities. Since JWST is unlikely to carry out a substantial direct imaging search for new planets during its primary mission, new discoveries and single young accelerating stars that emerge from our program will help make optimal use of this facility in the near future.

John Brewer / California State University, San Francisco
Third Rock: Finding the Terrestrial Planets Missing from RV Surveys

We learned from the NASA Kepler and K-2 missions that between ~20-50% of main sequence stars host small planets (having a radius between 1-4 Earth radii). Despite the short orbital periods of most of these transiting planet detections, similar detections of small mass planets have eluded radial velocity (RV) surveys. Rocky planets, even on short orbits, induce stellar velocities smaller than the 1-2 m/s precision of the previous generation of radial velocity instruments. With additional noise from stellar photospheres and typical RV observing cadences, even mini-Neptunes on months long orbits could have been missed.

This project will reconcile the different planet populations at periods less than 100 days seen by transit and radial velocity surveys by combining dramatically improved radial velocity precision with an extended high cadence observing program. We will also sample the occurrence rate of low mass planets at periods longer than 100 days that will be left unexplored by current transit surveys. It is in this space where Earth-like planets at habitable zone distances may be found around G and K stars.

The EXtreme PREcision Spectrograph (EXPRES) (Jurgenson et al. 2016) has demonstrated Doppler precision of better than 30 cm/s (Blackman et al. 2020, Petersburg et al. submitted). This precision is sufficient to detect the type of small rocky planets detected by Kepler. EXPRES is on the 4.3 meter, Lowell Discovery Telescope (LDT) where we have up to 70 nights/year that can be split as small as quarter nights for nearly 200 nights on-sky after accounting for normal losses due to weather. More than 2 years at that cadence are already banked with Lowell or have firm commitments from outside funding in addition to the year of science observations already obtained. Our program targets a rotating list of 45 stars that we observe at high cadence for several weeks before spacing them out to weekly observations, all at SNR~500. This strategy has already resulted in the detection of a short period mini-Neptune (Brewer et al. in prep) around a star with ~20 years of Keck HIRES observations.

The high precision, high resolution, and high cadence of our survey with EXPRES also enables characterization of planets and their host stars. We will be measuring spin-orbit alignments and atmospheres of small planets and characterizing the behavior of stellar photospheres. We have detected Fe II in the transit spectroscopy for a hot Jupiter, and measured the Rossiter-McLaughlin effect for a small planet orbiting a bright star. These discoveries reveal the intrinsic nature of planets, providing hints about formation and evolution. Co-I Llama will also be adding an additional 10-15 nights/year for RV follow-up characterization of TESS planets.

Finding and characterizing habitable exoplanets is one of the primary goals of NASA's Exoplanet Exploration Program (ExEP) Science Plan. Reconciling temperate rocky planet occurrence rates, and indeed all planetary architectures, between transit and radial velocity surveys is specifically identified as a priority in the ExEP Science gap list. This project will be unique in detecting low mass planets that have eluded other lower precision RV surveys and will improve our understanding of the complexity of multi-planet architectures.

Laird Close / University Of Arizona
A High-Contrast Survey of Young Stars for Accreting Protoplanets with the MagAO-X Extreme AO System: Defining the JWST Protoplanet Follow-up Sample

BACKGROUND: Today astronomers do not fully understand the complex process of gas giant planet formation or planet-disk interactions. There is strong evidence that the initial assembly of outer gas giants is very important to understanding the habitability of solar systems. Yet, it is almost impossible to use the present distribution of dynamically evolved planets (like the inner transiting systems discovered by the Kepler and TESS missions) to infer this initial distribution of gas giant orbits. We need a complete survey of young forming protoplanets to address these fundamental issues in exoplanet science.

OBJECTIVES: We will use the newly commissioned extreme adaptive optics (AO) system MagAO-X to discover a large population of "hidden" young accreting planets (protoplanets) in the gaps of transitional disks. This population will allow us to define a catalog of high-value follow-up protoplanets targets for NASA's JWST mission.

PROOF OF CONCEPT: We have already proven that young (<5Myr) gas giants pass through a period of high luminosity as hydrogen gas accretes onto their surface. Such an H-alpha signature can make the planet many orders of magnitude brighter at H-alpha than at H band (Close et al. 2014). This was unambiguously shown for the young protoplanet PDS 70 b in the center of the PDS 70 disk gap by our MagAO observations at H-alpha (Wagner et al. 2018). This H-alpha emission was independently confirmed by VLT/MUSE observations by Haffert et al. (2019) who also detected another outer planet PDS 70 c in the gap. It is, therefore, established that the accretion shock can be observed at H-alpha from multiple forming protoplanets in the gaps of transitional disks. We propose here to significantly improve on all past, rather low Strehl, H-alpha surveys by use of the new MagAO-X extreme AO system at the 6.5m Magellan Telescope in Chile. MagAO-X has many novel features (>1200 corrected modes, at >2 kHz loop speeds) that will enable Strehl ratios ~10x higher than currently available at H-alpha. MagAO-X is the only extreme AO system optimized from the start for working at wavelengths as blue as H-alpha. Moreover, its novel coronagraph and 3 deformable mirrors, allow for high-contrast H-alpha simultaneous differential imaging (SDI) with higher planet/star contrasts than ever before possible.

TECHNIQUES: We will use MagAO-X to carry out the largest survey of transitional disks for protoplanets with 2hr images at the strongest visible accretion emission line (H-alpha). We have very carefully selected the most optimal 20 southern (Dec<+35) young (<5 Myr) bright (I<13 mag) stars with transitional disks. The disk of each member of our sample has been independently vetted by ALMA imaging, and high-contrast coronagraphy, so that only those with large 20-80au cleared gaps in the dust are selected. This selection means that nearly all targets should have gap planets.

PRODUCTS: For each newly discovered planet the catalog will publish: planet orbit; est. mass accretion rate; est. mass; and predicted brightness in the NIR for JWST follow-up by the whole community.

SIGNIFICANCE: We have developed testable predictions about this population of planets with our massive accreting gap (MAG) planets model. We will be able to definitively answer if multiple planets clear most of the transitional disk gaps, and whether there is a large population of "cold start" wide (5-50 au) planets that have been missed by other direct imaging surveys. When the MAG model is applied to the measured on-sky contrasts of MagAO-X it predicts 20-46 new protoplanets should be discovered by our survey. That would be a tenfold increase in the number of known protoplanets and will jump-start the field of exoplanet science at the youngest ages. The catalog will enable expedited JWST follow-up, saving many hours of "blind" searching from JWST. Detection and characterization of exoplanets is very relevant to the NASA XRP program.

Ann Marie Cody / SETI Institute

From exocomets to technosignatures: hidden occulters in planetary systems

Over the past decade, NASA s space telescopes have scanned the sky for exoplanet transits and other variable phenomena. From Kepler and K2 to the Transiting Exoplanet Survey Satellite (TESS), these missions are finding thousands of planets around other stars. The photometric data are also enabling new studies of the origins and evolution of planetary systems. In particular, space photometry has shown that some stars display pronounced fading events due to occultations by material in orbit around them. The most prominent of these objects is KIC 8462852, also known as Boyajian's star. KIC 8462852 underwent a series of 1-20% flux drops over the course of the Kepler mission, prompting questions about the origin of occulting circumstellar material. Hypotheses ranged from star-grazing exocomet families to transiting megastructures built by an intelligent civilization. While the former idea is favored, investigation of Boyajian's star renewed interest in the search for technosignatures as a way of identifying life forms beyond our solar system. It also spurred investigation into the prevalence of comets orbiting close in to their parent stars, a handful of which were found with Kepler. Motivated by these discoveries, we are embarking on a project to quantify the frequency of anomalous fading events-- and hence occulting structures--among main sequence stars. Our objectives are two-fold: First, we will detect or put a stringent limit on the presence of transiting megastructures; second, we will assess the frequency of transiting minor bodies in planetary systems.

Our primary dataset for this work will be most of the TESS year 1 and 2 monitoring campaigns, which have covered nearly the entire sky down to 16th magnitude at 30-minute cadence for a minimum of 27 days per star. With a set of targets nearly two orders of magnitude larger than that of Kepler, TESS provides a can t-miss opportunity to harvest unusual fading variables and understand their origin. We will perform a comprehensive search for anomalous photometric fading events in this sample using automated statistical and machine learning techniques. After our initial work of identifying stars with anomalous brightness dips, we will turn to ground-based telescopes for multi-band photometric monitoring of further events; this color information will then be input into dust extinction models to determine the size of occulting grains. We also have access to radio telescopes taking part in search for extraterrestrial intelligence programs. Stars with anomalous variability that cannot be explained by astrophysics will be handed over as high-value targets. On the theoretical side, we will explore the structure of circumstellar material by creating and testing a series of models including exocomets with dusty tails, collisional debris rings, and megastructures with a variety of shapes and sizes.

Our work fulfills NASA s strategic astrophysics objectives to explore the origin and evolution of planets, as well as ultimately detect (or rule out) the presence of life on them. A detection of a technosignature would be profound, but (just as for currently-planned biosignature searches) a non-detection is the most likely outcome. However, the proposed study will enable us to place the most stringent limits yet on the presence of large artificial structures orbiting stars in our Galaxy, and correspondingly on the presence of technologically advanced life. Ultimately, we will provide a comprehensive catalog of occultation events observed around bright stars across the sky, as well as multiwavelength data that will be used to measure the size and geometry of associatedstructures, which can then be interpreted in the context of planetary system models. The range of amplitudes detected for occultation events will inform the calculations of the size range of exocomets, informing theories of exoplanetary dynamics as well as atmospheric bombardment.

Chuanfei Dong / Princeton University
Roles of Stellar Flares and Storms in Exoplanetary Atmospheric Losses and Evolution

Science goals and objectives: Research in exoplanets currently encompasses a wide spectrum of fields ranging from astrophysics to heliophysics and planetary science. One of the primary objectives in studying exoplanets is to understand, and quantitatively model, the chemical and physical processes that shape them. Among the manifold factors, understanding atmospheric losses and the concomitant atmospheric state and evolution is of paramount importance. Recent studies suggest that the stellar wind plays a significant role in scavenging the ionized gas from the upper atmosphere of exoplanets orbiting M-dwarfs. In addition, M-dwarfs are often highly magnetically active. Frequent stellar flares have been observed that produce a burst of radiation over a wide range of wavelengths, among which X-rays and extreme ultraviolet (EUV) constitute the major component of ionizing stellar radiation for planetary upper atmospheres at relatively low and high altitudes, respectively. Meanwhile, there has been increasing awareness that coronal mass ejections (CMEs) - sometimes termed as stellar storms - associated with stellar flares pose severe threats to planetary atmospheric retention. Until now, there are no systematic studies of the impact of stellar flares and associated CMEs on exoplanetary atmospheric losses and evolution. It is, therefore, our goal to study the role of stellar activities on exoplanetary atmospheric escape and the resultant evolution of the atmosphere for both Venus-like and Earth-like exoplanets and provide observationally-testable predictions (e.g., thermal phase curves, transmission and emission spectra) for NASA's upcoming JWST.

Methodology: We will employ the 3D BATS-R-US magnetohydrodynamic (MHD) model that has been extensively validated and applied to different solar system objects as well as exoplanets with different atmospheric compositions. The MHD model includes the whole ionosphere and the important ionospheric physics and photochemistry. The MHD model will adopt the upper atmosphere (i.e., thermosphere) from the Global Ionosphere-Thermosphere Model (GITM) that has been applied to various solar system bodies and exoplanets. The 3D thermosphere from GITM will incorporate the effect of stellar radiation during both quiet and flaring periods. It is noteworthy that the non-hydrostatic GITM can handle hydrodynamic escape if the atmosphere becomes hydrodynamically unstable. If the atmosphere is hydrodynamically stable, then the MHD model (using 3D GITM thermosphere) will compute the atmospheric ion escape rates based on the impact of either normal stellar winds or stellar CMEs if the latter coexist with flares (so both scenarios will be calculated). Even if stellar CMEs are suppressed, the dual effect of stellar winds and enhanced X-ray/EUV fluxes due to flares on exoplanetary atmospheric losses are worthy of investigation. We also plan to run a one-way interactive coupling between MHD, GITM, and LMD Generic GCM that enables investigating the state and evolution of planetary atmospheres via atmospheric losses. We will consequently provide the associated observationally-testable predictions for NASA's upcoming JWST. Finally, we will employ Alfven Wave Solar Model (AWSoM) to simulate stellar winds and stellar CMEs based on the observed magnetograms (or ZDI maps) of the host stars and stellar flare energies, respectively.

Relevance: The proposal is highly relevant to XRP as the proposed research is crucial for exploring and understanding the chemical and physical processes of exoplanets (including the state and evolution of their atmospheres). In addition, the proposed agenda has a significant impact on studying exoplanets through the development of observationally testable predictions. The proposal is also highly relevant to NASA's current and future missions (e.g., Kepler, TESS, and JWST) for the characterization of exoplanets and the study of their atmospheric states and evolution.

Steve Ertel / University Of Arizona
Studying the Habitable Zones of Nearby Main Sequence Stars with Precision Nulling Interferometry

The recent completion of the Hunt for Observable Signatures of Terrestrial planetary Systems (HOSTS) marks a major mile stone for the study of habitable zones (HZs) around nearby stars. We have surveyed 38 nearby stars to determine their warm dust content. This 'exozodiacal' dust, in analogy to the Solar system's zodiacal dust, is located in or near a star s HZ. We used nulling interferometry in the N band to suppress the star light and reveal faint, extended thermal dust emission. With a sensitivity to only a few times the Solar system's dust level for the most favorable targets and a detection rate of 26%, we are now able to study common exozodiacal dust.

The dust carries important information on the architectures and the dynamics of the bodies populating the inner regions of planetary systems. It may be produced by comets that can also deliver volatiles to terrestrial planets or destroy their atmospheres due to heavy bombardment. It can also reveal the presence of giant planets outside the HZ that may shield terrestrial planets against heavy comet or asteroid activity. Thus, the dust provides an important opportunity to gain insight into the environment in which potentially habitable planets exist. This will help prioritizing targets for exo-Earth imaging and for the time consuming spectroscopic characterization of detected candidates by evaluating whether a star's HZ is suitable for hosting habitable planets. Moreover, it will provide critical context for understanding why a characterized planet is habitable or not.

We request funding for people power to analyze incoming LBTI follow-up observations of the ten HOSTS detected exozodis. We are using the LBTI s well characterized and routine nulling interferometric mode to determine their exact dust levels, geometries, and temperatures (thus grain sizes). The HOSTS survey data were optimized for survey efficiency with snapshot observations carried out in the broad N band. They already suggest a large diversity of the dust geometries. Our new observing strategy is optimized for characterization: We obtain data in two well separated N band filters and with large parallactic angle coverage, maximizing the spectral and spatial information. Detailed dynamical and radiative transfer modeling will be used to break degeneracies in the data interpretation to constrain dust distribution, properties, and the nature, number, and dynamics of the dust s parent bodies. Generalizing our models will enable us to more reliably predict the amounts of HZ dust around other stars that were not surveyed from their known system properties such as stellar spectral type, mass and location of Kuiper and asteroid belts, and constraints on giant planets.

Our project directly addresses items Sci-4, -6, -9, -10, and -11 of the ExEP s science gap list. We respond to the goals to "characterize and explain the diversity of planetary system architectures, planetary compositions, and planetary environments" and to "to learn enough about the properties of exoplanets to identify potentially habitable environments and their frequency, and connect these environments to the planetary systems in which they reside" of the National Academy's Exoplanet Science Strategy report in which the LBTI and HOSTS were explicitly featured and that is the basis of ExEP s Science Development Plan. On the short term, our data will help planning exozodiacal dust observations (strategy, target selection) with WFIRST and provide highly complementary data for the interpretation of these scattered light data.

Jim Fuller / California Institute of Technology
The Turning Tide in Exoplanet Evolution

A crucial yet poorly understood step in exoplanet evolution is the tidal dissipation that molds short-period planetary orbits. Fortunately, the NASA missions Kepler, K2, and TESS are providing a nearly complete census of planetary populations at small orbital separations, along with accurate stellar and planetary properties, providing useful constraints for tidal migration theories. We propose to investigate three novel ideas in tidal theory that make readily testable predictions for exoplanet systems.

First, we will investigate the impact of tidal resonance locking on the orbital evolution of short-period planets. Resonance locking with stellar oscillations drives planetary tidal migration on a stellar evolution time scale, but it has never been considered for exoplanet systems. We will examine the impact of resonance locking on the inward migration of hot Jupiters, which predicts larger effective stellar tidal quality factors at short periods. We will also make predictions for the inward migration of lower mass planets at longer periods, and its significant effect on the planetary occurrence distribution versus orbital period. Additionally, we shall examine resonance locking with inertial waves and its effect on tidal spin-orbit alignment. Due to inefficient inertial wave dissipation in fully convective stars, spin-orbit misalignment of the lowest mass stars could remain large, similar to the larger average misalignments of planets around hot stars.

Second, we propose to study a new process called ``inverse tides, in which tidal interaction with a pulsating star can increase planetary eccentricity and obliquity as energy is tidally transferred from stellar pulsation modes into the planet s orbit. Our investigation will generate predictions for the eccentricities and obliquities driven by inverse tides for planetary populations around gamma Doradus and slowly pulsating B stars.

Third, we will examine the process of chaotic tides, in which planetary oscillation modes can be stochastically driven to large amplitudes for planets on highly eccentric orbits, allowing for rapid tidal circularization. However, low-mass planets may be tidally inflated, eventually leading to tidal disruption, while chaotic tides are likely inefficient for high planetary masses. We will study distinguishing trends in the population of planets resulting from chaotic tidal migration, predicting the upper and lower mass cutoffs expected for this mechanism.

Our work will combine computations of stellar and planetary oscillation modes, along with orbital evolution calculations, to solve for the coupled evolution of stellar structure and planetary orbital period/eccentricity. Confronting the predictions of these models with the short-period exoplanet populations discovered by Kepler, K2, and TESS will be essential to maximize the scientific return of these missions.

Yasuhiro Hasegawa / Jet Propulsion Laboratory
Metal enrichment of giant planets during their final formation stages

OBJECTIVES AND EXPECTED SIGNIFICANCE

We propose to model the final stages of giant planet formation and the subsequent evolution of planetary envelopes, focusing on the accretion dynamics of gas and planetesimals and on the resulting composition of the planets' atmospheres. The proposed calculations will model the detailed evolution of growing planets in gaseous protoplanetary disks, starting around the time when envelopes begin to collapse. During such phases, envelope contraction triggers rapid accretion of gas, which is eventually affected by the formation of a gap in the gas distribution. Importantly, the accretion of planetesimals on the planet is also affected by the evolving gas distribution. Henceforth, these two processes need to be modeled together. Accretion of gas and solids eventually determine the composition of giant planets' atmospheres. This proposal will shed light on some properties of the composition of massive exoplanets, by linking predictions from numerical models with current observations of giant planets' atmospheres.

TECHNICAL APPROACH AND METHODOLOGY

We will investigate how gas and solids are accreted by a forming planet using a state-of-the-art hydrodynamical code. In this part, we will increase the realism of the simulations by properly taking into account the dynamics of planetesimals, orbiting in a gaseous protoplanetary disk perturbed by the growing planet. By examining the complex interplay between the gas disk evolution and the orbital distribution of planetesimals, we will gain a firmer understanding of how gas gap formation around a growing planet influences the orbits of solids, and of how accretion of gas and planetesimals on the planet proceeds. We will examine how accreted planetesimals will behave in planetary envelopes, using state-of-the-art 1D planetary evolution codes. This will enable us to compute how thermal ablation of icy/rocky planetesimals takes place in the primordial atmospheres of planets, and to examine how the atmospheric metallicity of planets evolves with time. These computations will produce evolutionary tracks of the planetary radii. The proposed simulations will therefore provide us with some invaluable quantities (i.e., composition and radius constraints) for interpreting the observation of exoplanets' atmospheres.

While detailed simulations are necessary in this project, it is also important to examine the outcome of the simulations, using other approaches. To this end, we will derive new semi-analytical formulae for the accretion rates of planetesimals from the results of the proposed simulations. These accretion rates will be functions of planet mass and disk properties (e.g., disk viscosity, disk mass). Adopting such accretion rates, we will investigate how important planetesimal accretion is to reproducing the properties (e.g., the total heavy-element content trend) of observed exoplanets, compared with other processes.

RELEVANCE TO NASA PROGRAMS

This proposal will constrain physical processes operating during the final stages of giant planet formation. The results will produce detailed models of planet formation and atmosphere evolution, examined against observations of exoplanets. The proposed work will contribute to existing and ongoing efforts to understand the origins of exoplanets by Kepler, TESS, Hubble, and JWST (in the near future). Thus, the proposal directly addresses key goals of the Exoplanet Program, to "explore the chemical and physical processes of exoplanets and "improve understanding of the origins of exoplanetary systems".

Natalie Hinkel / Southwest Research Institute
Chemical Assessment of M-dwarfs and Their Rocky Exoplanets to Improve Characterization in the TESS/JWST Era

Driven by the NASA-directed search for Earth-like planets, we find that understanding whether a rocky planet may have atmospheric biosignatures requires a much-improved understanding of their geochemical cycles, which directly produce O_2 and CH_4. However, the stellar abundance data needed to model the interior and near-surface geochemical processes on the rocky planets -- which are more easily detected around cool M-dwarf stars -- is severely lacking. These abundances are used as a proxy for planetary composition, since stars and planets are formed from the same molecular cloud. However, M-dwarf spectra in the optical band are dominated by molecular features (VO and TiO) which make abundance measurements difficult. Infrared M-dwarfs spectra have a more well-defined continuum, but suffer from telluric absorption, such that the available absorption features are not well characterized relative to optical lines. As a result, only a few elements (e.g. C, N, O, Ca, and Fe) have been measured within a small number of M-dwarf stars (~120 stars), meaning that we are unable to determine large-scale chemical trends that link the stars with their planets.

In this proposal, we will develop an infrared abundance pipeline that is specifically tailored to model the physics within cooler, M-dwarf stars. We will base the pipeline on the observations and subsequent abundance measurements of elemental and molecular lines in 22 M-dwarf stars hosting 40 planets. We will utilize ground-based, infrared instrumentation, specifically IGRINS (HK-band) -- on which we have guaranteed time through the UT consortium (such that 14 target spectra will be in-hand by may 2021), as well as iSHELL on IRTF. By using the abundances of the host star, we will apply the thermodynamically self-consistent ExoPlex mass-radius software package and its planet classification scheme to our sample of M-dwarf planets, taking into account all measured uncertainties. These models will statistically test how compositionally similar the exoplanets are to their host-stars. Planets consistent with the composition of the host star can be classified as rocky planets. Planets that are chemical discrepant from the host star require special geochemical circumstances to explain their differences (e.g., mantle stripping or significant H2 atmosphere). We will also include within our sample any new TESS or JWST M-dwarf planets, with established planetary masses and/or radii, discovered during the time frame of this proposal. Our agnostic planetary classification scheme will allow us to more confidently assess the interior structure, mineralogy, and geochemical cycles on these M-dwarf planets.

This project will help fulfill one of the primary goals of the NASA Exoplanet Research Program, namely to "explore the chemical and physical processes of exoplanets (including the state and evolution of their surfaces, interiors, and atmospheres)" while also "observationally characteriz[ing] exoplanets, their atmospheres, or specific host star properties that directly impact our understanding of the exoplanetary system." More specifically, this proposal will allow us to build the tools necessary to chemically characterize M-dwarfs and their rocky planets in an unprecedented manner. Ultimately, we will build the machinery necessary to provide a clear star-rocky planet chemical link, paving the way for faster, easier planetary classification for current and future NASA mission targets.

Julie Jung / Triad National Security, LLC
New Spectroscopically Accurate Line Lists for Brown Dwarf Atmospheres: Completing the Dataset for FeH.

High resolution, space-oriented spectroscopic technologies play a central role in exoplanet exploration. They provide vital information on the chemical composition, hydrodynamics, and structure of both exoplanets and their host stars. In order to access such information, it is essential to have accurate spectroscopic data for astrochemically relevant species. In that context, FeH is a major player. It is a key contributor to the near infrared spectrum of brown dwarfs (750-2500 nm), at temperatures of 1000-3000 K . Hence, it is of interest for both detection and characterization purposes. In particular, its unique spectroscopic signature (i.e. large number of sharp and isolated absorption lines, with high magnetic sensitivity) makes it a valuable diagnosis tool for magnetic field measurements. Hence, we propose to determine spectroscopically accurate line lists for the FeH molecule and its isotopologues, to improve such analysis.

Our goals are the following:
- Determine the molecular constants for the electronic states and transitions of FeH. Our focus will be on bands associated to transitions seen in the infrared region, haven t been studied as intensely as the F-X (or Wing-Ford) band because they overlap with telluric contaminations. Yet, the new generations of space telescopes (e.g. JWST and WFIRST-AFTA) is expected to overcome this issue by providing high-resolution data in the near and mid infrared region. We will rely on a combination of state-of-the-art quantum chemistry methods and available laboratory measurements, including magnetic characterization, to calculate molecular constants for the FeH states below 25,000 cm-1.
- Determine spectroscopically accurate line lists for FeH transitions. This will be achieved by solving the nuclear motion equation, using the aforementioned molecular constants. Special care will be taken to describe the Zeeman interaction (i.e. coupling of the angular momenta with the rotation of the molecule through a magnetic field) by computing the Landé g-factors for the individual states. Magnetic fields of a few kG are typically measured by measuring differences in the Landé factors of different lines. The larger the Landé factor, the bigger the sensitivity.
- Determine magnetic fields from either polarimetric or intensity measurements. To do this, we will (a) compare the relative magnetic sensitivity of the different lines, (b) evaluate the ratio of highly vs. slightly sensitive lines, and (c) test our findings against observational data available from mission archives (i.e. near infrared spectra of brown dwarf atmospheres).
We plan to take advantage of NASA-provided High-End Computing Resources.
Due to their abundance in the Milky Way, and their resemblance with Sun-like stars, brown dwarfs have a high potential to host Earth-size exoplanets in their habitable zone. Since important aspects of planetary habitability are determined by the properties of the host star, the present research, which supports the characterization of brown dwarfs, will advance exoplanet science, and improve our understanding of exoplanetary systems. Indeed, knowledge of stellar companions is needed to properly interpret exoplanet properties, but also for modeling purposes (e.g. hydrodynamics and radiative transfer of the planets orbiting around them). Knowledge about the magnetic field of host stars is of prime importance, as it is known to affect planetary atmospheres and magnetospheres, which are thought to be essential in providing a protective

shield crucial for the evolution of life. The signature of FeH can also provide information about radial velocity, rotation, active areas and solar winds on brown dwarfs. By extending and improving existing data, the proposed work will help fill the knowledge gap about intrinsic stellar properties, and more precisely brown dwarfs (e.g. variation of the magnetic field with stellar temperature, and surface composition and inhomogeneities), and thus, exoplanets.

Theodora Karalidi / University Of Central Florida
A suite of tools for characterizing Imaged exoplanets using high resolution spectropolarimetry

The imminent launch of the James Webb Space Telescope in collaboration with the Very and Extremely Large ground-based telescopes is expected to revolutionize our understanding of exoplanet atmospheres. For the first time we will have access to high-resolution, broad wavelength-coverage observations of exoatmospheres, with unprecedented high signal-to-noise-ratios (SNR). This will allow us to constrain the atmospheric properties of exoplanets, such as their composition and cloud content and their temporal evolution for the first time, and open a new window in the study of exoatmospheres.

Experience from our own Solar system though, suggests that flux only observations suffer from degeneracies, and ground- and space-based polarimetry observations from the current and future telescopes (with instruments such as SPIROU, CRIRES+, HiSpec and POLLUX to name a few) will be needed to break those degeneracies. A number of exoatmospheres have been observed to date that show significant polarization, and even polarized rotational variability. However, no grid of models exists to date that allows us to characterize high-resolution spectropolarimetric observations.

We propose to create the first grid of high-resolution polarimetric spectra of Directly Imaged exoplanets. For the creation of the grid we will use a state-of-the-art code that can calculate in a self-consistent way the temperature-pressure and composition profile and cloud profiles of an atmosphere of any arbitrary composition and then will calculate its full spectropolarimetric signal. We will then use an instrument simulator (PSISIM) on our models to test the detectability of spectral features by current and future ground- and space-based instruments. PSISIM is a python-based instrument simulator with a flexible framework, built for translating theoretical spectra and polarized spectra into SNR estimates based on bulk instrument properties. It currently includes modes for HiSpec, MODHIS and has plans to expand to more instruments in the near future. Finally, we will invert the modeled observed spectra to create the first retrieval algorithm for polarimetric observations of exoplanet atmospheres. We will test our retrieval algorithm on existing polarimetric observations of exoatmospheres that our team has access to.

Our proposed research will create a powerful suite of tools to characterize the spectropolarimetric signal of Imaged exoplanets and uniquely complement current characterization tools, allowing us to break degeneracies on the characterization of existing and future exoatmosphere spectropolarimetric observations. Our proposed research will, e.g., enable us to characterize the microphysical properties of clouds on directly imaged exoplanets, accurately constrain their cloud top pressures and break degeneracies in the location of clouds in exoatmospheres that flux-only observations have. Our proposed research will finally enable the strategic planning of observations of directly imaged planets, and the designing of future space telescopes. The proposed research aims to create a suite of tools that will help the community characterize and understand the physical processes that govern exoplanet atmospheres and is thus directly relevant to the NASA XRP call.

Quinn Konopacky / University Of California, San Diego
Moderate Resolution Spectroscopy of Directly Imaged Exoplanets: Abundances, Kinematics, and Algorithms for the Era of JWST

In the past decade, a new generation of extreme adaptive optics surveys on large (8-10 m), ground based telescopes have revealed a small but intriguing population of gas giant planets orbiting at large distance (>10 AU) from their host stars. This population of directly imaged planets has offered tantalizing hints about the typical separations and sizes of Jovian planets. Perhaps more importantly, this population is amenable to traditional spectroscopic observations, offering an unprecedented view of young gas giant atmospheres.

The photometric and/or very low resolution spectroscopic data provided by the discovery observations of directly imaged planets 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. Our group has pioneered observational and theoretical techniques that have provided spectra at resolutions and SNR 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 abundances of individual elements in the planets, such as carbon and oxygen. More recently, we have demonstrated advanced post-processing techniques that have allowed for the measurement of radial velocities, opening a new window into the kinematics of these widely separated companions.

To-date, our focus has been on the near-infrared K band (~2.2 um). We have compiled a library of R~4000 K band spectra for nine directly imaged planets using the integral field spectrograph OSIRIS at the W.M. Keck Observatory, and computed grids of models to analyze them, deriving both atmospheric and kinematic properties. As we have pushed our observations to the limits of what is possible, several new puzzles have arisen. These include the true planet metallicity and the evolution of disequilibrium chemistry with temperature and age. We therefore propose to advance our efforts with a pivot to new wavelength regimes. We will gather and analyze R~4000 spectra in near-infrared J and H band from the ground with OSIRIS. These spectral regimes provide access to higher atomic number species, such as potassium, that can shed light on the abundances of elements beyond carbon and oxygen. We will provide a full library of all spectra obtained with OSIRIS for further study by other groups using a variety of models.

At the same time, we will prepare for the capabilities afforded by JWST, which will offer longer wavelength (3-5 um) coverage at similar spectral resolution with the NIRSpec IFU. These wavelengths uniquely probe disequilibrium chemistry due to the strong methane features in this region. Our group will generate and analyze synthetic NIRSpec data cubes and apply our advanced post-processing algorithms to them in order to prepare for surveys of directly imaged planets with NIRSpec. All algorithms and synthetic data generated will be made available for the entire community to utilize.

The research proposed here is highly relevant to the NASA Exoplanets Research program. We will provide a framework for measuring atmospheric properties of directly imaged planets with JWST, which can be adapted for future missions such as the Nancy Grace Roman Space Telescope or LUVOIR. We will also directly contribute to identified exoplanet science gaps SCI-02, "Modeling exoplanet atmospheres", and SCI-03, "Spectral signature retrieval" by generating models that can be used to characterize a wide range of exoplanet atmospheres, and directly challenging them with new datasets spanning multiple wavelength regimes.

Timothy Livengood / University of Maryland, College Park
Spectroscopy and Lightcurves of Terrestrial Exoplanet Analogs: Earth and Mars from the EPOXI Discovery Mission

The proposed effort will analyze unpublished measurements of Earth s whole-disc rotational lightcurve and spectrum from a polar vantage point that have not otherwise ever been empirically measured, as well as Mars ecliptic-plane observations acquired by identical means. The Mars measurements enable a direct comparison between Earth and Mars spectral features and lightcurves to investigate the ability to distinguish their habitability and other properties. These data pose direct empirical constraints that can be applied to exoplanet modeling tools by validating their applicability to Earth and Mars. A limited amount of such work has been accomplished for equatorial plane data from this dataset. The present work will result in tabulated results for lightcurves, spectra, and phase-angle for Earth polar observations and for Mars that will be suitable to validate continuing developments in modeling tools for exoplanet emergent spectra and lightcurves (e.g., Merrelli et al. 2019; Robinson et al. 2011). The reported data encompass features such as atmospheric water vapor content, carbon dioxide abundance, ozone abundance, air temperature, ground temperature, the vegetation red edge, albedo, surface mineralogy on Mars, and rotation rate that are of deep interest to astrobiology in characterizing exoplanet properties. No other data set exists to constrain whole-disc models for these features observed from a polar vantage point for Earth, or for ecliptic-plane Mars. The present work does not propose to investigate such models, but rather to create tabulated numerical information that is accessible to creators of such models.

In 2008-2009 the Deep Impact planetary science spacecraft, within its EPOXI extended mission under NASA s Discovery program, conducted observations of Earth and Mars as analogs to terrestrial exoplanets. Data from this work has contributed to several papers characterizing rotational modulation of lightcurves in the visible, but considerable work remains to be performed since the end of support under Discovery. Specifically, near-infrared modulation has not been published to express the nature of data that can be acquired in this range, as well as planetary phase function for Earth and a limited amount of such data for Mars in visible and near-IR wavelengths, characterization of the vegetation red edge in polar-oriented observations, identification of other features distinguishing Earth and Mars as terrestrial planets, one habitable and one (apparently) not. The EPOXI data all are available from the Planetary Data System (PDS) Small Bodies Node (PDS/SBN), including Mars data that were acquired during the post-EPOXI phase before spacecraft failure in August 2013 that have never been characterized or published.

We will evaluate empirical whole-disk spectroscopy, spectrophotometry, and lightcurve features of Earth and Mars as analogs for exoplanets in reflected light at visible through near-IR wavelengths. This work will identify features that convey fundamental information about these bodies and the signal-to-noise level required to distinguish them. Direct observation of terrestrial exoplanets in reflected light is on the technological horizon, no longer a distant prospect. Designing capabilities to characterize terrestrial exoplanets requires the best possible guidance for measurements that can be achieved and that can achieve significant scientific results.

Mercedes Lopez-Morales / Smithsonian Institution/Smithsonian Astrophysical Observatory
ACCESS: Ground-based, High-Quality Optical Transmission Spectra of Exoplanets to Optimize and Complement Exoplanet Atmospheres Observations with JWST

The atmospheres of about 40 exoplanets have been observed so far with a striking result: exoplanet atmospheres appear widely diverse, and there is no clear correlation between their properties and any other system parameters. It is now clear that we will only understand the physical and chemical properties of exoplanet atmospheres by comparing large statistically samples of targets. This will require large amounts of observing resources, including ground-based.

NASA's TESS and JWST will revolutionize exoplanet atmospheres studies by finding the most suitable targets for atmospheric characterization around bright stars, and by observing the atmospheres of a myriad of planets over a large wavelength range. JWST observations will be key to establish atmospheric properties, but will need observations in the optical to reveal a complete picture. Blue-optical data will be particularly critical to establish cloud/haze levels in the atmospheres of these planets to measure accurate chemical abundances. Initial observations in the optical of newly discovered planets can also identify the best clear-atmosphere targets for further detailed characterization with JWST. HST has played a major role in producing UV-Optical observations, but it is now clear that adding ground-based facilities with long-term access to large amounts of telescope time, and therefore many targets, will be the only way to enable large statistical studies.

ACCESS is an ongoing survey on the 6.5 meter Magellan Telescopes to measure 0.4 0.9 micron transmission spectra of gas giant exoplanets. As a collaboration, we have access to about 80% of the Magellan time. ACCESS has already produced precise transmission spectra of eight planets, and observations of several other planets are in-hand or underway. Our team has pioneered statistical frameworks for joint analyses of exoplanetary atmospheric and stellar contamination features in transmission spectra. We also produced the first optical ground-based transmission spectra with better precision than HST.

We propose to produce precise, optical transmission spectra of three sets of exoplanets using a low-resolution optical spectrograph on the Magellan Telescopes. The first set consists of seven planets with approved GTO and ERS transmission spectroscopy observations with JWST. Our spectra, combined with JWST s will establish the cloud/haze coverage baselines to measure unbiased atmospheric chemical abundances. The second set consists of the best 5-6 TESS gas giant exoplanets around nearby stars for future detailed atmospheric characterization. The third set is a group of six twin exoplanets identified to have almost identical system parameters except for the metallicity of their host stars. These observations will provide the first test of a controlled sample of planets to investigate if metallicity differences in different planet formation environments can explained observed differences in atmospheric cloud properties.

Our observations will provide enabling datasets of optical transmission spectra to 1) maximize the science output of already planned JWST observations of transiting exoplanets, 2) identify the best gas giant exoplanets from TESS for extensive atmospheric follow-up with JWST and future ELTs, and 3) help identify correlations between observed atmospheric properties and system parameters.

The impact of our results on current and future NASA missions will be significant: First, we will provide key observations to disentangle expected degeneracies between atmospheric composition and cloud/haze coverage in the set of exoplanets currently planned to be studied with JWST. Second, we will identify for the community which newly-discovered TESS planets are best suited for extensive atmospheric follow-up. Third, we will increase the number of exoplanets with observed optical transmission spectra to enable statistical studies of how their atmospheric properties depend on other system parameters.

Andrew Mann / University Of North Carolina, Chapel Hill
How often are newborn planets aligned with their host stars?

Many planets have been found to be on orbits highly misaligned from their host stars. Exoplanet studies often assume such spin-orbit misalignments originate from gravitational interactions with more distant planets or stars. However, this assumes that the planets formed aligned, and therefore must be a product of later evolutionary processes.

The sites of planet formation, protoplanetary disks, are natural products of the star formation process. It is natural to expect the rotational axes of young stars to be aligned with their flat protoplanetary disks; this reflects the structure of our Solar System and fits with simple angular momentum arguments. However, models of protostellar disks suggest this picture is far too simple. Disks can form or become misaligned through interactions with other stars or their environment. These processes can completely reorient a disk, and operate on timescales of tens or hundreds of thousands of years, much faster than the planet formation processes. Unfortunately, we have few observational constraints on the occurrence of misaligned or warped disks. Thus, we cannot make statistical statements about the relative importance of more secular processes on the orbital evolution of planets compared to processes that operate on the disk from which they formed.

We propose a study into the disk-star alignment of a large sample of co-eval stars, utilizing uniform datasets from K2 and TESS, updated stellar models ideal for young stars, disk inclinations from ALMA, and rotational broadening estimates from a new high-resolution spectrograph ideal for studies of young systems. Our goal is to measure the frequency of misaligned planet-forming disks at multiple ages during the planet formation process. Our result is critical to inform studies of spin-orbit (mis)alignment in mature planets and could change our understanding of the origins and formation of planetary systems.

Jean-Luc Margot / University of California, Los Angeles
A search for technosignatures around newly discovered exoplanets

I propose to conduct a search for technosignatures around ~100 newly discovered exoplanets with the largest fully steerable telescope in the world. This investigation will address one of the most important scientific questions of our time: are we alone in the universe? It will address NASA's strategic objective to "search for life elsewhere" while expanding the search from primitive to complex life and from the solar neighborhood to the entire Galaxy. We will search for narrowband (<10 Hz) emission and sample a different slice of the search volume than that of all previous surveys. Our search is sensitive to Arecibo-class transmitters located within 420 light years of Earth and to transmitters that are 1000 times more effective than Arecibo located within 13,000 light years of Earth. It relies on a successful observational strategy developed over the past 5 years and a data processing pipeline that has key advantages compared to other pipelines. In particular, we archive all raw data to preserve the ability to reprocess the data with improved algorithms or search for different types of signatures in the future. In addition to conducting the search, I propose to develop three data analysis tools and make them available to the community. We will address the biggest challenge to radio technosignature searches the excision of radio frequency interference (RFI) by using the remarkable ability of deep neural networks to perform classification tasks with high accuracy. We will develop two machine learning tools to enhance RFI identification and classification. We will also develop a signal injection and recovery tool that can rigorously quantify the efficiency of data processing pipelines. This tool is an essential but currently missing ingredient that will enable researchers to discover imperfections in their data processing pipelines and improve the estimation of existence limits for transmitting civilizations. An important component of this investigation is to help train the next generation of bio/technosignatures researchers and big data scientists. I propose to train a graduate student as part of this investigation and to expose approximately 5-10 graduate students and 75 undergraduate students to portions of the work during an annual 10-week technosignatures course offered at UCLA since 2016. In summary, I propose to accomplish the following three specific objectives: (1) Search for narrowband radio frequency emission around ~100 main sequence FGKM stars harboring newly discovered exoplanets; (2) Develop and share a signal injection and recovery tool and machine learning tools for improved signal classification; and (3) Train a graduate student in observational astronomy, signal processing, big data analysis, and machine learning techniques. I have two decades of experience in observational astronomy, radio science, and the analysis of large data sets. I seek to continue engaging the public and building the technosignature community. This investigation will enable sensitive observations that will probe ~100 planetary systems for signs of intelligent life. It is a high-risk, high-impact project with the potential for profound advances in human knowledge.

Rebecca Martin / University Of Nevada, Las Vegas
Formation and evolution of misaligned disks and planets in binary star systems

Most planets are in binary star systems and thus understanding planet formation in binaries is essential for explaining observed exoplanet properties. Planets form in and around the binary in circumstellar and circumbinary disks, respectively. Observations indicate that such disks may form misaligned with respect to the orbital plane of the binary. A misaligned circumbinary protoplanetary disk around an eccentric binary evolves either towards coplanar or towards an orientation that is perpendicular to the orbital plane of the binary (polar alignment), depending on the disk and binary parameters. We propose to form a complete understanding of circumbinary disk evolution and hence the initial inclination distribution for circumbinary planets. We will investigate how the evolution of a gas disk affects the dust within it and implications for planet formation in misaligned circumbinary disks. We will explore the stability of misaligned circumbinary planetary systems. A circumstellar disk around one component of a binary evolves towards coplanar alignment in the absence of accretion on to the disk. However, circumbinary disks may feed the formation of circumstellar disks around each binary component. The accretion of high inclination material affects the dynamics of the circumstellar disk that may lead to long lived Kozai-Lidov oscillations of the disk eccentricity and inclination. We propose to investigate the formation and evolution of circumstellar disks from a misaligned circumbinary disk. Finally we will consider the evolution of dust in a disk undergoing Kozai-Lidov oscillations and implications for planet formation in highly misaligned circumstellar disks. We propose to study these processes by means of analytic, one-dimensional, and three-dimensional simulations. The results will provide insights into the origin and current state of circumbinary planets and highly inclined and eccentric planets in binaries.

Neil Murphy / Jet Propulsion Laboratory
Space weather impacts on habitable exoplanets

The impact of stellar activity on exoplanet atmospheres and near-surface plays an important role in the evolution of the exoplanet s environment, and may have important consequences for the development and sustenance of habitability. Studying exoplanet-host star interactions requires understanding the factors affecting the host s stellar wind (e.g. composition, speed, density, and temperature), the energetic particle and UV/EU fluxes it produces, and how these factors vary with time. As has been found from the study of space weather in our own solar system, these quantities vary on multiple timescales, with a wide dynamic range. In addition we need to understand how exoplanets will respond to this vaying plasma environment, depending on such factors as planetary mass, composition, distance from the host star and how strongly magnetized an exoplanet is. Gaining this understanding is a fundamental focus of NASA s exoplanetary science program.

Using current characterizations of exoplanetary atmospheres, and ground-breaking measurements to be made by the James Webb Space Telescope, together with state-of-the-art stellar wind and planetary magnetospheric models, we can address this problem with a new level of detail, accurately simulating the exoplanetary plasma environment and characterizing its impact on exoplanet atmospheres.

To address this, we will answer the following:
1) How does the stellar wind-magnetosphere coupling vary for different stars and stellar winds? Under what circumstances will an exoplanet s interaction with its host star affect habitability?
2) How does the strength of planetary magnetization affect atmospheric loss rates and coupling to the stellar wind?
3) How does the composition of an exoplanetary atmosphere affect its dynamics and loss rate?
4) What are the potential impacts of stellar energetic particle fluxes on exoplanet surfaces?

We will use advanced magnetohydrodynamic simulations developed for studies of solar wind evolution and planetary interactions to understand the conditions of stellar winds and their radial evolution, and include insights gained from the recent Parker Solar Probe mission. This will be done for several exoplanetary systems with planets in their habitable zone, beginning with the TRAPPIST-1 system.

We will also model the stellar wind interaction with the exoplanet system, to simulate the stellar wind-magnetosphere-ionosphere coupling to better understand the interaction and to estimate atmospheric loss of these exoplanets. This will be completed for a variety of model exoplanetary magnetic field strengths. Differing magnetization will result in different atmospheric loss rates and by comparing to atmospheric observations we may be able to constrain the magnetization of an exoplanet.

This proposal will contribute directly to XRP s objectives which include:
"characterization of exoplanetary systems; characterization of individual exoplanets, through their composition, dynamics, energetics, chemical behavior, etc." and to "Explore the chemical and physical processes of exoplanets (including the state and evolution of their surfaces,

interiors, and atmospheres)”.

This proposal is multidisciplinary, covering planetary and heliospheric science to better understand exoplanetary systems, falling within the XRP statement of scope: “proposed investigations that combine multiple scientific disciplines or cross traditional Divisional science boundaries are encouraged”

Erik Petigura / University of California, Los Angeles
The Origins, Dynamics, and Architectures of TESS Planets

Motivation:
One startling result from NASA s Kepler mission was that nearly every Sun-like star has a small planet between the size of Earth and Neptune. Given the lack of such planets orbiting the Sun, we now know that the solar system is not a typical outcome of planet formation. Accordingly, in the post-Kepler era, we are now compelled to ask: Why does nature produce super-Earths and sub-Neptunes so efficiently? and Why do we lack such planets in our own solar system?

Just as the architecture of the solar system played a profound role in the development of planetary astrophysics, the architectures of super-Earth/sub-Neptune systems will continue to advance planet formation theory. Here, architecture refers to the sizes, shapes, spacings, and orientations of planet orbits, as well as how planets are ordered in terms of size and mass. While there is no doubt of the ubiquity of small planets, there are significant gaps in our understanding of their architectures, due in large part to the lack of suitable radial velocity (RV) datasets. In particular, few sub-Jovians mass planets have well characterized eccentricities, and thus the eccentricity distribution is poorly understood. In addition, it is unclear whether there is an interrelation between Kepler-type small planets and distant Jovians. Here, we propose to conduct two Doppler surveys of small TESS planets to fill in these gaps and illuminate the origin of small planets.

Methods:
The TESS mission is currently discovering large numbers of small transiting planets around bright stars that are amenable to detailed RV characterization. Our group has initiated the TESS-Keck Survey (TKS), a large RV survey anchored around Keck/HIRES, with supplementary observations from the Automated Planet Finder (APF). TKS is built around the union of several distinct science themes and the participation of many team members across the Keck community.

Working within the TKS collaboration, we will conduct two RV surveys to characterize the architectures of TESS sub-Jovians. The first will map out the upper envelope of small planet eccentricities by pre-selecting high-eccentricity candidates using the photo-eccentric effect. We will then collect RVs to pin down their eccentricities along planet mass, envelope fraction, and presence of other planets. These quantities will provide clues regarding the dynamical pathways that lead to high eccentricities, along with constraints on important tidal properties like the tidal quality factor, Q.

In our second survey, we will gather RVs at moderate cadence, roughly once 1 per month for 3 years, of a large sample (N=60) of TESS-detected small planet hosts. This survey will measure, among other things, the conditional occurrence of Jovians in systems with small planets. This quantity is currently poorly constrained because known small planets and Jovian analogs are drawn from nearly disjoint stellar samples. Our survey will probe important planet formation processes such as the drift of solids and gas in the protoplanetary disk. We will also learn whether the familiar size ordering of the solar system planets---with the small planets close-in and the gas giants farther out---is a common outcome of planet formation.

Relevance to the XRP:
Our proposal supports NASA s strategic goals to characterize the diverse population of small exoplanets and directly supports the scientific yield of NASA s investment in the TESS mission, as well as those of the Kepler, K2, JWST, WFIRST, and HabEx/LUVIOR missions. It is relevant to the specific XRP call in that we will detect [&] and confirm exoplanets as well as observationally characterize exoplanets (specifically their architectures), which will lead to an improved understanding of the origins of exoplanetary systems.

Elisa Quintana / NASA Goddard Space Flight Center
A Uniform Catalog of Planets from TESS Full Frame Images

The Transiting Exoplanet Survey Satellite (TESS) is the first near-all-sky photometric survey and currently provides the only opportunity to probe exoplanet demographics across the sky and over an extremely broad parameter space. In the 2-year TESS prime mission (July 2018-July 2020), approximately 200,000 pre-selected stars will be observed at 2-minute cadence, but over 80 million stars brighter than 15th magnitude will be observed at 30 minute cadence with Full Frame Images (FFIs). Exoplanet yields for TESS predicted over 4,300 planets orbiting bright dwarf stars, with 3,100 of these expected to be found with FFI data. While TESS is on its way to achieving its mission goals of finding 50 planets smaller than Neptune amenable to mass measurements, the overall TESS planet yield is lagging significantly behind predictions, due largely to a dearth of planets from the FFIs (fewer than 500 of the 1,300 planet candidates were found with FFI data).

We propose a multifaceted program to unleash the full power of TESS by (1) creating and releasing FFI light curves from 23 months of TESS data for all stars down to 15th magnitude, (2) searching for planet candidates around all stars brighter than 13th magnitude and cool dwarfs brighter than 15th magnitude using three independent planet search pipelines, (3) publishing the results in a comprehensive, uniform catalog of well-vetted planet candidates, (4) measuring the completeness and reliability of the catalog based on well-tested techniques designed for Kepler, (5) exploring the demographics of the intrinsic exoplanet population as a function of stellar type, age, and environment.

These FFI data represent 2 orders of magnitude more stars than Kepler/K2. To assist with the vetting of the large number of planet candidate signals we expect to detect from the millions of stars we will search, we will develop a citizen science project "Planet Patrol" that will classify planet candidates based on vetting metrics. These user classifications will be used as input for a machine-learning based classification scheme to improve the automated disposition of planet candidates.

We will address specific science questions that can only be studied with a well-vetted catalog of planet candidates with measured catalog completeness (the fraction of true transiting planets detected) and reliability (the fraction of transiting candidates that are not caused by instrumental or stellar noise). One remarkable finding from the population of Kepler planets is the lack of planets with sizes between 1.5 and 2 Earth radii orbiting Sun-like stars. We expect to find hundreds of new TESS planets with sizes that straddle this radius gap, around both low mass stars and high mass stars, which will allow us to determine whether the radius valley holds for stars smaller and larger than the Sun. We will also measure the occurrence rates of planets of all sizes as a function of stellar properties and location on the sky, and determine whether they match estimates made previously with the Kepler and K2 missions.

Steven Saar/Smithsonian Institution/Smithsonian Astrophysical Observatory

The Devil's in the Details: Clearing the Path to Exo-Earths Through Deeper Understanding (and Mitigation) of Stellar Surface Phenomena Masking Their Detection

To fully characterize exo-earths (Earth mass, ~1 year orbit), radial velocity (RV) measurements are required. However, the accuracy of RV measurements seems stuck at ~1 m/s, >> the 20 cm/s needed for success. Most of the blame lies with stellar variations, largely magnetic in nature, which mask the planetary signals.

We propose to crack this "RV barrier" by a multipronged approach. First, we have identified several solar magnetic activity effects which are not accounted for in current RV removal methods. Three are velocity fields associated with magnetic areas that flow tangent to the surface: penumbral flows, moat flows, and active region (AR) inflows. Penumbrae are the warm outer part of sunspots (~250 K cooler than the photosphere), with 3/4 of the total spot area, and having ~2 km/s radial outflow. Moat flows are radial outflows of ~750 m/s which lie just outside of spots, with about 3x the spot area. The third flow, AR inflows, are strange flows in the quiet Sun, directed partly towards AR from the N and S, and partly counter-rotation. While the weakest of the flows (~20 m/s), AR inflows cover a much larger area (~2-4x that of its AR). Our preliminary models indicate these flows all deliver non-sinusoidal RV variations (making them harder for current methods to model), and that the AR inflows will dominate.

Three final elements lie outside current modeling: the RV effect of flares, line asymmetries, and magnetic intensification (MI). The first is likely unimportant for many FGK targets, but may be significant in M dwarfs, warranting their study. MI, which arises due to the increase in equivalent width of stronger absorption lines in the presence of a magnetic field (B), is notable for its complex dependence ~W*A*B^2, where W is the wavelength and A is the magnetic area. Finally, line asymmetries are largely ignored (modeled with symmetric Gaussians). Better accounting for them (and their variation with B) should improve RVs.

We plan to study all of these effects. We want to extend our current simplistic flow models to arbitrary latitudes and inclinations, and use them to explore how best to correct for the activity induced RV using available tracers. We will study the effect of flares empirically using solar SDO data. We will explore using asymmetric functions in the RV determination procedure; "global line bisectors" will be extracted as an additional diagnostic tool. In all cases, our models will be tested against HARPS-N solar RV observations, with AIA/HMI data on spot, plage, and flow locations as input. Solar data will be used to develop an empirical "G2 star model kit", using statistics on solar SDO HMI velocity data, and AIA location/size data. This "model kit" will allow the user to construct semi-empirical G2 stars with arbitrary activity, and study the resulting output RV signal to, e.g., test RV mitigation schemes.

Haywood et al (2020) found that the unsigned magnetic flux Phi_B provided the best diagnostic for RV variations; a second major goal will be to significantly improve the minimum Phi_B detectable and its precision. Simultaneous multi-line (>100) modeling of line profiles and MI looks to be a promising route; we argue we should be able to reach Phi_B ~ 10 G on bright stars by this method. The procedure will also yield estimates of B and A separately, useful for the flow and MI RV modeling. As a backup, we will determine plage and spot A using selected moluecules (CN, CH, and TiO).

The combination of these studies, models for new RV phenomena and new/better diagnostics to trace them, will significantly improve RV precision. Initial tests combining a crude AR inflow model and simplified MI effects within the Haywood et al scheme already improves RV precision to sigma_RV ~ 0.6 m/s over their (~7 year) dataset. We seem to be on the right track; this proposal will allow us make further progress.

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To have but not to hold: Atmospheric mass loss of Super-Earths and Sub-Neptunes

Scientific Motivation and Goals
In the last decade, NASA's Kepler mission has revolutionized the field of (exo-)planetary science by discovering more than 4000 planetary candidates. One of Kepler's key findings is that the most abundant planets in our galaxy, observed to date, are larger than Earth but smaller than Neptune. Intriguingly, further observations have revealed a radius valley' in the distribution of such small exoplanets with periods less than about 100 days. Smaller planets with higher densities are consistent with rocky Earth-like compositions while larger planets with lower densities suggest that they are engulfed in large H/He atmospheres. Studies have suggested that the valley likely marks a transition regime from a population of super-Earths': smaller, rocky planets, to a population of sub-Neptunes : larger planets with significant H/He atmospheres. Both photo-evaporation (e.g. Owen & Wu 2017) and the core-powered mass-loss mechanism (e.g. Gupta & Schlichting 2018) appear to explain the observed radius valley and related observations. Under both of these mechanisms, the smaller and closer planets lose their entire

primordial atmospheres, while the larger and further away planets retain some of their atmospheres. As both mechanisms seem to be an inevitable part of planet formation and are not distinct processes, we will focus on combining photo-evaporation models and core-powered mass loss models. Currently, photoevaporation models simply assume the base of the flow is attached to the underlying static planet s atmosphere and the core-powered mass-loss mechanism does not include heating from XUV photons. By performing a combined core-powered mass-loss and photoevaporation calculation we will determine which region the sonic-point (XUV vs bolometrically heated) sits and hence which mechanism is important in different regions of parameter space. This work will determine the importance of atmospheric mass loss due to these two different mechanisms and their combined effect will be directly compared with the observed super-Earth and sub-Neptune population. Combing photo-evaporation models and core-powered mass loss models is crucial to correctly interpret observations of the radius valley in the exoplanet size distribution, to infer the physical properties of the underlying exoplanet distribution and to make testable predictions for future observations.

Relevance to Exoplanets Research Program
In the proposed work we seek to investigate the atmospheric mass loss of super-Earths and sub-Neptunes. Specifically, we will focus on combining the photo-evaporation models and core-powered mass loss models. This work will determine the importance of atmospheric mass loss due to these two different mechanisms; it will determine when one mechanism is expected to dominate over the other and it will determine the total expected mass-loss over an exoplanet s lifetime. Since both these models were developed explicitly to explain the observed exoplanet population it is clearly relevant to XRP. The proposed work directly addresses the stated Exoplanets Research program goals to explore the chemical and physical processes of exoplanets (including the state and evolution of their surfaces, interiors, and atmospheres) and to improve understanding of the origins of exoplanetary systems .

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Adaptation of high precision atmospheric trace gas retrieval technique and updated spectroscopy to model micro-telluric features enabling EPRV

Measurements of Precision Radial Velocity (PRV) of host stars provides complementary information on the characteristics of exoplanets, such as orbit eccentricity, mass, density, etc. When combined with PRVs, the transit method enables empirical constraints on the internal structure and composition of exoplanets. The Exoplanet Science Strategy (ESS) report highlighted the importance of the Extreme Precision Radial Velocity (EPRV) technique to detect Earth analog planets in support of direct-imaging flagship missions (e.g., HabEx and LUVOIR) for follow-up observations toward to determine the bulk composition and surface gravity of these planets.

However, there is no spectral region free of telluric lines, which primarily originate from ro-vibrational transitions from infrared-active atmospheric molecules (i.e., H2O, CH4, CO2, O2). Thus, the telluric lines became the limiting factor in RV precision, for example, to 1 - 3 m/s in the NIR. Moreover, accurate modeling of the telluric water lines is extremely challenging because (1) the water transitions are virtually everywhere and highly congested in the spectrum, and (2) its concentration keeps changing spatially and temporally in an unpredictable way and on short time scale. This issue has been very well recognized in the White Paper Report on Radial Velocity Prospects Current and Future by the Exoplanet Program Analysis Group (ExoPAG).

Thus, we propose an innovative approach to be able to remove tellurics. We will leverage the state-of-the-art expertise in Earth atmospheric remote sensing and high-resolution molecular spectroscopy (laboratory measurements and theoretical calculations). Starting with the existing state-of-the-art atmospheric trace gas retrieval program, GFIT, we will develop its extended version, Stellar-GFIT, adopting an advanced molecular line shape model to fit telluric features in the stellar spectrum. In parallel, we will update the spectroscopic database in the aimed spectral region, i.e. 1.8 0.6 ¼m. For this, we will conduct (a) task-specific laboratory measurements and (b) theoretical calculations for H2O and CH4, and (c) continuous repairing any missing or inaccurate parameters in the existing linelists (e.g., HITRAN and an in-house cherry-picked linelist, ATM161). We will apply the Stellar-GFIT and the updated spectroscopy to fit out the telluric absorption features from the stellar spectrum from multiple locations (Palomar, Kitt Peak, Mauna Kea) in NIR and VIS regions. The proposed approach will enable fitting telluric features to a high-precision (~1% of fitting residuals) through rigorous independent adjustments of all trace gas concentrations involved during spectrum fitting. Finally, we will generate telluric-free PARVI and NEID spectrum sets, based on which we will review several techniques to the PRV measurements and make realistic error budgets in the PRV measurements. We expect, as a result, the maximum absolute values of the micro-telluric interference impact for the G, K, and M stars to be improved to 0.1 m/s or the claimed instrumental precision (e.g., 0.3 m/s in case of the PARVI spectrum), esp. when the advantage of the broad-band spectrographs of PARVI and NEID is fully utilized.

EPRV would be the most direct direct way of characterizing the masses and orbits of low mass planetary systems. Furthermore, since the ground-based EPRV measurements will be a vital complement to transit missions such as TESS, CHEOPS, and PLATO.