Exoplanet Research Program
Abstracts of selected proposals
(NNH15ZDA001N-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 16, 2015, 20 proposals were selected for funding.

Fred Adams/University of Michigan
Ionization Processes in Young Stellar Objects: Effects on Circumstellar Disks and Planet Formation

Circumstellar disks provide the birth places for planets and disk properties constrain the possible architectures of the resulting planetary systems. The formation, evolution, and eventual demise of circumstellar disks represents an ongoing problem in studies of star and planet formation. This proposal will address a collection of physical processes that affect the ionization levels in circumstellar disks and will determine the corresponding observational signatures. The results of this work will be an improved understanding of disk structure and the initial conditions for planet formation.

Ionization levels in young stellar objects are determined by many sources, including cosmic rays (CRs), short-lived radioactive nuclei (SLRs), and photons. In our Solar System, CRs are modulated by the solar wind, which suppresses CR fluxes within our Heliosphere. We will develop analogous models of CR suppression for young star/disk systems, which have more powerful winds. We will also generalize magnetic mirroring of CRs by including turbulent fluctuations. Given the potential suppression of CRs, we will consider alternate ionization sources, including SLRs and high energy radiation (specifically X-rays and EUV).

The project will also consider how ionization levels influence disk structure and evolution. Ionization fractions determine the regions in the disk where MRI is active and hence where disk accretion can take place. In addition, ionization affects chemical processes, which determine the location of snow-lines in the disk and the dominant carriers of various elements of interest (e.g., carbon and oxygen). Finally, ionization levels determine the chemical makeup of the disk gas, which can be observed by Spitzer, Herschel archival data, ALMA, JWST, and other facilities; this project will calculate the observational signatures of the expected (varying) ionization levels.

This project will conduct a theoretical investigation of the effects of ionization on disk evolution and the implications for planet formation. The project will be carried out by the PI, the Co-I, two scientific collaborators, and a graduate student funded under the auspices of the project. The work will take place at U. Michigan and will involve both the Physics and Astronomy Departments.

Planet formation involves a large number of steps, from the formation of the parental cloud to final planetary properties. In this chain of creation, results from one physical process provide the initial conditions for the next. This project studies the effects of ionization on circumstellar disks, which provide the initial conditions for the buildup of planets. Ionization affects the snow-lines in the disk and thereby influences the chemical composition of bodies forming at different locations. Ionization also affects the viability of MRI, which influences both disk accretion and planet migration. The cosmic rays, photons, and SLRs that determine the ionization levels also contribute to heating in the disk gas and heating within coalescing bodies. All of these processes must be understood in order to develop a coherent theory of planet formation -- a fundamental goal of this program.

Philip Armitage/JILA
Ice lines and ionization edges as catalysts for planet formation

Objectives: The simplest models for planet formation assume that the first step in the process - planetesimal formation - occurs across a broad range of protoplanetary disk radii. This assumption may be false. Theoretically, it is known that sharp changes in disk structure occur at the radii where ices first condense (at the snow line and CO ice line), and at the ionization edge close to the star where temperatures allow thermal ionization of the alkali metals. These locations have been suggested to be propitious sites for the accumulation of solids and the rapid formation of planetesimals. Observationally, it is now known that planetary systems containing super-Earths and mini-Neptunes at small orbital radii are extremely common. This has motivated consideration of models where planet formation is favored close to the star, at radii roughly coincident with where the ionization edge sits.

The goal of the proposed research is to conduct a detailed first principles study of the evolution of solids, and the formation of planetesimals, in the vicinity of icelines and ionization edges. We will specifically model the structure of protoplanetary disks, and the response of small solid particles (ranging from dust to mm and cm-sized bodies) to that structure, in the region of the alkali metal ionization front (at $T \sim 1000$ K), the water snow line (at $T = 150$-170 K) and the CO iceline (at $T \sim 20$ K). We will determine whether and when planetesimal formation is favored at these locations, and thereby assess whether there are disk conditions under which the bulk of early-stage planet formation is catalyzed at specific disk radii.

Methods: We will use numerical magnetohydrodynamic (MHD) simulations, that include the relevant non-ideal MHD processes, to directly model the turbulence that determines the gas structure near icelines and ionization edges, along with how solids diffuse relative to the gas. These capabilities have already been developed. Also following existing studies, the evolution of solids under aerodynamic forces (radial drift and turbulence) will be modeled using an explicit particle description. As part of the new work we will develop and add the capability to model the "chemical" processes (sublimation,

condensation and thermal ionization) that are critical for understanding the structure of disks near icelines and ionization edges.

Relevance to the Exoplanet Research Program: It is known that most of the planetary systems cataloged by Kepler, which commonly contain super-Earth and mini-Neptune planets in short-period orbits, cannot have formed in the same way as the Solar System's terrestrial planets. Migration was clearly a dominant factor in the assembly of these systems, but whether this involved fully formed planets, or small solids that drifted to small radii before forming planetesimals, is unclear and debated. The part of the proposed work that deals with ionization edges (which addresses the second possibility) will thus explore a possibly dominant channel of extrasolar planet formation. The part of the work on icelines will likewise study what may be the main way of forming giant planets at larger orbital radii, which is relevant to future direct imaging / coronographic missions that will survey for exoplanets on scales beyond the snow line.

Edwin Bergin/University of Michigan
The Evolution of the Volatile Inventory in Gas-Rich Planet-Forming Disks

Overview of Science Goals: The early stages of planetary birth, settling of dust to a dust-rich midplane, lead to the sequestration of solids a gas-rich disk. Beyond the respective snowlines volatiles (such as CO, H2O, N2) will condense as ice coatings on refractory materials and become incorporated into any forming planetesimals. Over time this process must deplete the upper atmosphere of volatiles, such as water, CO, and N2. These species would normally emit in the surface layers where temperatures can drive sublimation or where ices are photodesorbed. Using Spitzer and Herschel data, we have recently found evidence for this physical-chemical process in TW Hya, the closest planet-forming disk. In this disk we find that the abundances of H2O, O, OH, and CO need to be reduced in the emissive upper layers. We suggest that the main elemental reservoirs of these volatiles resides deeper in the disk, toward the midplane, mostly likely as pebbles or planetesimals. Here we propose a combined theoretical and observational effort to characterize this process, its timescales, and search for mass-independent chemical signatures. The implications of this work are broad as estimates of disk gas mass and gas dissipation timescales from species such as CO will be intertwined with the timescales of planet formation. Moreover, evidence for this process itself bears information on the disposition of the very elements (C, H, O, N) that are key to the formation of habitable planets.

Methodology: As part of this program we will run several thousand physical/time-dependent chemical models spanning parameter space, and develop/implement prescriptions for planetesimal formation and ice sequestration. The abundance and emission predictions from this grid will provide an understanding regarding the fate of key carriers/tracers of the C, H, O, and N elemental pools, and determine observable, mass independent, signatures of planetesimal formation and/or gas phase chemical processing. Our observational efforts will characterize evolution through targeting sources sampling a range in age. Thus, we will use the Spitzer/Herschel archive, our

Keck archive, the ALMA archive, new Keck spectro-astrometric data, accepted ALMA Cycle 1 and 2 programs, plus new proposals for ALMA Cycle 3 and NOEMA, and compare these data to our theoretical grid to characterize the overall spatial distribution of key volatiles such as CO, H2O, HCN, and N2 (via NO and N2H+) and their links to planet formation. Crucially we have seed data sets to study disk chemistry in two sources that span a range of ages to shed light on these effects. Our program includes a dedicated effort to use the knowledge gained by this program and provide a spectral database for JWST.

Relevance: The exoplanets research program includes a focus to "improve understanding of the origins of exoplanetary systems." This proposed program is centered on the chemical side. Our observations have revealed evidence for a chemical evolutionary process in protoplanetary disks, which we posit is associated with the early stages of planet formation. This proposal also has direct relevance to NASA missions as we will mine the Spitzer and Herschel archives for available data, while we also focus on predicting spectra for JWST. Through characterization of the gas phase composition we will also infer the disposition of main molecular carriers of C, O, and N frozen as ices. It is these ingredients that are the seeds to habitable worlds, while the gas composition sets the stage for the composition of the gas giant atmospheres. In our models we will track C/O and C/N ratios in gas and ices under a range of environmental parameters and evolutionary effects. This will directly inform on the interpretation of exoplanet atmospheric compositions.

Peter Bernath/Old Dominion University
Spectroscopy for Super-Earth Atmospheres

Observations of the atmospheres of “hot” super-Earth exoplanets are underway in many research groups but their interpretation requires suitable reference spectral data based on laboratory measurements. The theme of this proposal is the laboratory spectroscopy of molecules of importance in the atmospheres of super-Earth exoplanets including hot H2O, LiF, AlCl, AlF, NO and TiO. We will deliver spectroscopic line lists based on both experiment and ab initio calculation for these species. Experimental observations are made with a high resolution Bruker Fourier transform infrared spectrometer using a high temperature furnace source. Our data can be used for identification of molecules and simulation of exoplanet spectra. In the Exoplanets Research program, the proposal will help to “interpret observations of exoplanetary systems”. We note that current NASA missions such as Kepler K2, Spitzer (warm phase) and HST are used to study these objects. In the future JWST will result in the characterization of large numbers of exoplanets, and a number of planned missions such as TESS (Transiting Exoplanet Survey Satellite) and WFIRST-AFTA also target exoplanets. In addition, NASA is funding the Extreme Precision Doppler Spectrometer for exoplanet observations at the WIYN telescope at Kitt Peak, AZ.

Geoffrey Blake/California Institute of Technology
Direct Characterization of Exoplanet Atmospheres using High Resolution Infrared Spectroscopy

Science Goals and Objectives: We propose to use high-resolution, near-IR, ground-based spectroscopy to directly characterize Neptune- and Jupiter-sized exoplanets that closely orbit their host stars. Our scientific objectives include directly measuring, at high spectral resolution, individual molecular species (including, but not limited to, H2O, CO, and CH4), and, in conjunction with radiative transfer models, to constrain the atmospheric composition, temperature profile, structure, and energy transport. Our methodology does not require the planet to transit, and thus can access the large population of nearby hot-Jupiter systems. The data also directly measure the semi-amplitude radial velocity of a planet's orbit. For multi-planet systems, this informs investigations of coplanarity.

Methodology: We have an established ground-based observing campaign that uses the Keck NIRSPEC echelle spectrograph to target nearby close-in planets with high-spectral resolution. Observations are taken at wavelengths from 2 - 5 microns, where the molecules of interest (CO, H2O, CH4, etc.) have clearly distinguishable features. Our spectroscopy captures the blended light from a planet/star system on multiple epochs, corresponding to different orbital phases, and achieves photon signal-to-noise levels on the stellar light of several thousand per resolution element per epoch. The individual planet and star signals are disentangled using cross-correlation based techniques, which leverage the radial velocity of a faint companion to separate it from a bright host. We utilize highly customized synthetic stellar and planet spectra as templates in our correlation analysis. By adjusting the chemical and physical parameters of the planet spectrum, we can independently probe different molecular species and atmospheric structure. This approach can minimize degeneracy in the planet models that pose serious problems for many low-resolution and photometric studies that have occurred over the past decade. We have demonstrated the viability of our methodology and published a 3 micron detection of water vapor in the atmosphere of the hot-Jupiter planet tau Bootis b (Lockwood et al. 2014, ApJL, 783, L29). In ongoing work we have also found that sufficient signal-to-noise in our wavelength regime can be obtained on targets with host stars as faint as L~6.5 magnitudes, which makes available a population of more than a dozen known exoplanet systems. Substantial numbers of additional targets can be expected from TESS and ongoing ground-based campaigns. We will analyze the observational data using a newly-developed, self-consistent atmospheric retrieval framework, SCARLET. Unlike previous methods, SCARLET combines the physical and chemical consistency of complex atmospheric models with the statistical treatment of observational uncertainties known from atmospheric retrieval techniques. In particular, SCARLET will permit us to fully probe the multidimensional parameter space spanned by the metallicity (that is, the overall abundance of heavy elements), the C/O ratio, and physical properties such the internal heat, surface gravity, and cloud fraction.

Relevance of the Proposed Research: The proposed research is highly relevant to the Exoplanets Research Program goal of: "understanding the chemical and physical

processes of exoplanets." Direct measurements of molecular species in the atmospheres of hot gas-giant exoplanets strongly constrain the overall atmospheric chemistry of these objects, and are critical towards understanding both the origins and subsequent evolution of planetary systems. Additionally, directly detecting the radial velocity signatures of these planets facilitates a dynamical measurement of the true planet mass and informed estimates of the planet radius, both of which are critical probes of the physical processes at work during planet formation.

William Danchi/NASA Goddard Space Flight Center
Direct Imaging and Interferometry of Proto-planets at the Epoch of Disk Clearing

Goals and Objectives:
At the present time approximately a dozen directly imaged (r > 8-9 au) giant exoplanets are now known, most associated with young stars such as beta Pictoris, with age estimates ranging from 20-100 Myr. Circumstellar disks with indirect signs of the presence of giant planets and ages < 10 Myr are known as a result of on-going high-contrast imaging studies on 8-m class ground-based telescopes (Grady et al. 2014). Follow-on studies have begun to yield data on their young, giant planets, as well as indirect signatures of their presence and effect on their natal disks, which may constrain the properties of these planets. Our main goal is to extend these imaging studies to mid-IR wavelengths, in particular L, M, and N bands, where planet candidates may be found within wide or annular gaps in the disks, or in small spiral structures, which are local hotspots in their disks. We will perform high angular resolution imagery and interferometry of these disks, extending observations to much smaller spatial scales than could be reached before, into the terrestrial planet forming zone within a few au of the host star. The mid-IR is advantageous because the thermal emission from a forming proto-planet is expected to enhance the planet-to-disk and planet-to-star contrast, compared to that available at shorter wavelengths where the planet signal is swamped by the disk.

Methodology:
We will use archival data and we will also compare the imagery with spectroscopic observations of molecular gas to constrain cavity sizes and identify planets, which may have circumplanetary disks. We will perform new observations in these bands using new powerful instruments including the Large Binocular Telescope Interferometer (LBTI), and LMIRCAM at the LBTO, the MagAO system at the Magellan Telescope, and starting in the second year of the proposed effort, the Multi-AperTure mid-Infrared SpectroScopic Experiment (MATISSE) instrument. MATISSE is a mid-IR spectro-interferometer combining data from up to 4 Unit Telescopes (UTs) or Auxiliary Telescopes (ATs) of the Very Large Telescope Interferometer (VLTI). It simultaneously acquires data at L, M, and N, providing critical wavelength coverage at wavelengths where protoplanets are expected to peak in brightness, angular resolution of ~ 3 mas at L, and sufficient (u,v) plane coverage to permit image reconstruction. MATISSE will install at the VLTI in Fall 2015, with GTO observations (Lopez, Matter, Danchi) expected to begin in 2017, in the second year of the proposed study period. We will augment these

data for more northerly systems using the LBTI, which will provide angular resolution of the order of 15 mas at L. LBTI is a working instrument with nulling and aperture masking and direct imaging modes at L and N bands. Ground-truth for the shorter wavelength interferometry will make use of conventional L' imagery and state of the art observing and data reduction techniques. This effort will make use of available archival data and new observations such as can be obtained with LBT/LMIRCam (Hinz and Eisner) and MagAO (Weinberger), and will also compare the imagery with spectroscopic observations of molecular gas to constrain cavity sizes and identify planets, which may have circumplanetary disks (Brittain). To aid in the interpretation of the data we will use various radiative transfer codes such as Whitney's code (co-I Sitko) and the new RADMC3D code of Dullemond (Matter, Danchi, Lopez).

Relevance:
Our investigation will advance knowledge and understanding of exoplanetary systems by performing new, unique observations to: (1) detect new previously unknown young exoplanets and their effects on their parent circumstellar disks; (2) interpret the observations by comparing imaging and spectroscopic observations as well as using radiative transfer modeling to obtain the physical conditions in the disks; (3) and improve our understanding of the origins of exoplanets.

Rebekah Dawson/Pennsylvania State University
Warm, Large Exoplanets

Extra-solar planetary systems have surprised us with their dramatic differences from planets in our Solar System. Among the most mysterious in origin are planets with orbital periods 10-200 days and sizes larger than Neptune's. Such Warm, Large Exoplanets (WaLEs) have been more easily discovered than their smaller and/or longer-period counterparts, yet they are challenging to account for theoretically. Their large atmospheres, short orbital periods, and large ranges of mass and eccentricity have posed a puzzle to theories of how planetary systems form and evolve.

WaLEs are the easiest planets to characterize apart from hot Jupiters but have been studied in much less detail, making them ripe for first order discoveries. The Kepler Mission discovered a rich sample of approximately 90 WaLE candidates that have not yet been studied systematically. Furthermore, WaLEs will be readily discovered by the {Transiting Exoplanet Survey Satellite (TESS)} and are prime targets for atmospheric characterization by the {James Webb Space Telescope (JWST)}. Therefore now is a critical time for a detailed population study of WaLEs to establish the context of their properties and origins. We propose to investigate through the following avenues:

1. Simulations of the dynamical and tidal evolution of planetary systems that can transform planets formed at larger separations into WaLEs. We will specifically conduct a parameter study of a mechanism -- a flavor of Kozai-Lidov oscillations with tidal friction that involves a nearby, eccentric, mutually inclined planetary

perturber -- demonstrated to be promising for producing the population of WaLEs on elliptical orbits discovered by radial-velocity (RV) surveys.
2. Using data from the Kepler Mission, constrain the eccentricities, transit timing variations, and transit duration variations of WaLEs, cataloguing both detections and upper-limits. Place limits on eccentric warm Jupiters' perturbers using published radial-velocity data. We will then compare to the predictions generated by our parameter study to test the mechanism above.
3. Use our resulting catalogue to assess architectures, orbital properties, and stellar properties as a function of planet size, determining whether a dependence on the WaLE's size is evident.

Relevance to the Exoplanet Research Program: This proposal uses transit and radial-velocity observations to constrain the orbital architectures of planetary systems, supporting the NASA Exoplanets Program goal of "interpreting observations of exoplanetary systems" and "characterization of exoplanets and exoplanetary systems... including determination of their dynamics." This proposal supports the goal of "improving understanding of the origins of exoplanetary systems" by testing mechanisms for the origins of WaLEs. Our results will elucidate the origins and properties of a category of planets that are relatively easy to characterize but have not yet been studied systematically.

Jonathan Fortney/University of California, Santa Cruz
Connecting Stellar and Planetary Composition: A New Window on Planet Formation

Objectives: We aim to understand the connection between stellar abundances derived from the photospheres of planet-hosting stars and the bulk metal-enrichment of their transiting giant planets. For a small sample of planets it has been shown that iron-rich parent stars harbor more metal-rich giant planets, and that this enhancement in planet metallicity (as derived from planetary bulk density) is a strong function of planet mass. This same pattern is seen in the solar system, where super-solar bulk metal enhancement increases from Jupiter, to Saturn, to Uranus and Neptune. Here we will dramatically increase our sample size to better understand the robustness of this important correlation for exoplanets. For the first time we will also pair this modeling work with spectroscopic studies of the parent stars to determine the stellar abundances and hence "starting conditions" of the planet-forming elements beyond iron, including silicon, nickel, magnesium, oxygen, and carbon. These efforts will provide new and unique insights into giant planet formation. Our overall goal is to derive the "mass-metallicity relation" for giant planets assess its dependence on particular stellar abundances.

Methodology: The major undertaking will consist of two separate but entirely complementary projects. One is a modeling study to infer the bulk heavy element enrichment of planets, based on their radius evolution over time. There now exists a sample of 40+ planets below Teff~1000 K, which are cool enough that they are not anomalously "inflated," such that their bulk metallicity can be constrained with the aid of

thermal evolution/contraction models, from the planetary mass, radius, and stellar age. At a given mass and age, planets that are more metal rich are smaller and denser. For this same sample, we will obtain high-resolution optical spectra with Keck HIRES in the north and Magellan MIKE in the south to derive parent star abundances. We will have a particular focus on the potentially most important planet-forming elements, Si, Ni, Mg, O, and C. Any correlations (or lack thereof) between stellar elemental enrichments and planetary bulk enrichments will give us a window into the composition of the metals within the planets. For instance a weaker correlation between stellar [C/H] and planetary enrichment (compared to stellar [Fe/H] or [O/H], for instance) would suggest the carbon is not important in giant planet formation, contrary to suggestions about Jupiter's formation and composition. The observations will also be used to provide a more robust assessment of total parent star metallicity.

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

Lee Hartmann/University of Michigan
Initial Distributions of Angular Momenta and Magnetic Flux for Protoplanetary Disks

We propose to:

1) use magnetohydrodynamic simulations of molecular clouds to follow protostellar core and sink (star) formation starting from large scales, enabling us to predict the amounts and frequency distributions of angular momenta and magnetic fluxes imparted to cores;
2) apply the initial conditions derived from the large scale simulations to a limited set of small-scale calculations of protostellar disk formation, as first steps toward understanding the distribution of initial disk properties;
3) post-process the simulations with radiative transfer codes to compare with observations of protostellar cores and infall to disks in a variety of molecular tracers as well as dust, and test the results against constraints on gas kinematics, as well as magnetic field strengths and orientations relative to the angular momentum axes;
4) and provide the data cubes resulting from the simulations to the community for further theoretical studies of disk formation, as well as for comparison with observations of collapsing protostellar envelopes and protoplanetary disks.

This program supports the Exoplanets Research goal of ``improve understanding of the origins of exoplanetary systems'' specifically by improving our understanding of the origin of variations in disk masses, sizes, and lifetimes; these properties impact the formation, evolution, and migration of planets, and thus help produce the diversity of the resulting exoplanetary systems.

Sarah Horst/ Johns Hopkins University
Exploring Cool and Hazy Exoplanet Atmospheres in the Laboratory

Science Goals and Objectives

Although it has long been postulated that clouds and hazes were important components of exoplanet atmospheres, it is only recently that observations have substantiated their existence. Clouds and/or hazes have been detected at high significance in the atmospheres of the super-Earth GJ1214b (Teq~600 K), Neptune-mass GJ436b (Teq~800 K), and hot-Jupiter Kepler-7b (Teq~1700 K). In the case of Kepler-7b in the high temperature regime, equilibrium silicate clouds provide an adequate match to the observe variations in the planetary albedo as a function of orbital phase. The nature of the clouds/hazes in the atmospheres of GJ1214b and GJ436b are more uncertain, as thick equilibrium cloud species are not expected to form this temperature regime. Thus far there are no observational indications that photochemistry (either haze formation or disequilbrium chemistry) strongly affects planets hotter than 1200 K. It is expected that photochemistry will play a much greater role in the atmospheres of planets with average temperatures below 1000 K, especially those planets that may have enhanced atmospheric metallicity and/or C/O ratios such as super-Earths and Neptune-mass planets. The Kepler mission has shown that the most populous type of planets are those for which we have no solar system analogs, super-earths (1.25 Rearth < Rp <2.0 Rearth) and mini-Neptunes (2.0 Rearth < Rp < 4.0 Rearth). The TESS mission will substantially increase the number of super-Earths and mini-Neptunes on which atmospheric characterization studies can be conducted. However, these studies will require improved experimental constraints on photochemical processes in these cooler metal-rich planetary atmospheres. Although models of atmospheric photochemistry and haze optical properties provide good first estimates, they are incomplete and biased by available solar system data. Laboratory production of exoplanet hazes is a crucial next step in our ability to properly characterize these planetary atmospheres. The proposed study would represent the first laboratory tests of haze formation in exoplanet atmospheres in this important temperature range.

Here we propose to investigate photochemical processes cooler metal-rich exoplanetary atmospheres in a state-of-art laboratory facility specifically designed to investigate a range of planetary atmospheres. Our laboratory experiments will produce photochemical hazes (as well as gas phase products) whose composition can be further studied using mass spectrometry. We will investigate the effect of gas composition, temperature, and energy source on the formation and physical/chemical properties of haze.

Michael Jura/UCLA
Extrasolar Cosmochemistry

The generally accepted standard model for the presence of elements heavier than helium in the atmospheres of white dwarfs cooler than 20,000 K is that these stars have accreted

tidally-disrupted asteroids. As a zero-order approximation, it has been found that as with bulk Earth, the major constituents are oxygen, magnesium, silicon and iron. No truly exotic objects -- such as being carbon/silicon dominated or being calcium/aluminum/oxygen dominated -- have been found. Consequently, it seems that geophysical models for the origin and evolution of rocky objects developed for the solar system may be extended to extrasolar planetesimals.

We propose to address three specific questions that cannot be addressed with any other technique and which are central for understanding the origin and evolution of rocky planetesimals:

(i) How well can we constrain interior models of extrasolar rocky planets?
(ii) Why does the oxygen over carbon abundance ratio vary by more than a factor of 1000 among extrasolar planetesimals?
(iii) Is there any evidence for plate tectonics on extrasolar planets?

Joel Kastner/Rochester Institute of Technology
Multiwavelength Studies of the Nearest Known Protoplanetary Disks

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

Methodology: The program we propose to conduct under NASA Exoplanets support includes optical/near-IR adaptive optics coronagraphic/polarimetric imaging to elucidate the dust density structures of the nearest known protoplanetary disks within their giant-planet-forming regions, with resolution on scales of a few AU; submm/mm-wave imaging and spectroscopy to establish the residual masses, structures, and chemistries of the gaseous components of nearby, molecule-rich disks within their outer, proto-Kuiper-Belt zones; X-ray and optical/near-infrared spectroscopy targeting the central stars and star-disk interaction regions; and modeling of dust and gas disk structure and chemistry that is informed and constrained by the foregoing groundbreaking observational campaign. Our team has already compiled a successful track record that spans all of these program elements.

Relevance & significance: The proposed multiwavelength study of nearby protoplanetary disks represents a fundamental step toward understanding the origin of our solar system and, ultimately, life on Earth, and toward explaining the breathtaking diversity of exoplanet systems. In characterizing the physical conditions within gas-rich protoplanetary disks orbiting young stars in our "back yard", we expect to inform and constrain theories describing the processes governing giant planet and Kuiper Belt formation. We will also be able to better assess the likely signposts of recently formed (age 20 Myr or less) planetary systems and, hence, increase the likelihood of detection of such a "newborn" solar system. Thus, the proposed program is very well suited to the goals and objectives of the NASA Exoplanets Research program.

Edwin Kite/University of Chicago
Origin of the Volatile Envelopes of Small-Radius Exoplanets

Understanding the origin of the volatiles is fundamental to the interpretation of discoveries from the Kepler, K2 and TESS missions, as well as future observations of planets and planet-forming disks with the James Webb Space Telescope. Measurements of densities and masses for Kepler planets indicate that many small-radius planets contain significant volumes of volatiles. However, the relative contributions of water versus nebular-disk hydrogen to these planets' volatiles inventories are not understood for most small Kepler planets. Current observations are consistent with either hydrogen accretion from the nebular disk onto rock cores, or hydrogen production via iron oxidation at water-rock interfaces (outgassing). These two divergent scenarios have very different implications for planet formation, evolution, and habitability.

We will test the H2-production hypothesis by combining basic models of planet thermal evolution and outgassing with a modern dynamical model incorporating disk migration. Specifically, we will model the rock-volatile interfaces of rocky cores as they grow and migrate, accounting for water-rock reactions, surface-interior recycling, volatile partitioning between magma and atmosphere, and hydrogen loss to space, both before and after the dispersal of the gas disk. We will consider two scenarios: (1) a "maximal production" scenario in which water is delivered to the cores in quantities that maximize hydrogen production (and thus planet radii), (2) a 'dynamical' scenario in which the supply of water is set by dynamical models for radial mixing of small bodies that are enriched in water due to the location of their condensation relative to the ice line. In our "dynamical" scenario, we will explore a two dimensional parameter space varying the total disk mass in solids, and the convexity of the solid body growth rate as a function of orbital distance (which affects radial drift/orbital migration). In both scenario (1) and scenario (2) we will self-consistently track pressure, temperature, and rock composition at the volatile-rock interface and their effect on H2 production, and set accretion of nebular H2 to zero. Thus, we shall obtain both: (1) strict upper limits, and (2) realistic estimates, for the radii of planets with atmospheres produced primarily via water-rock reactions.

We will compare the results of our calculations to constraints for the abundance of volatiles for small planets discovered by Kepler, K2, and eventually TESS, incorporating mass constraints from Radial Velocity (RV) observations and analyses of Transit-Timing Variations (TTV). For planets with radii measured to exceed our calculated radii in the "maximal production" scenario, we will obtain a lower bound on the contribution of nebular accretion to the volatile inventory of those planets. These results will lead to constraints for disk lifetimes, disk dynamics and astrophysical-metal enrichments of those planets (at their birth annuli). For planets with radii measured to be consistent with our model, we will predict their hydrogen:water ratios. Planets for which our model predicts large hydrogen:water ratios would not have Earth-like atmospheres, irrespective of our assumption of minimal nebular accretion. Therefore, our model will offer a valuable tool for assessing which planets could plausibly have an Earth-like atmosphere. Applying our model to small planets that lack mass and density measurements (e.g., in or near the habitable zone of Sunlike stars and thus beyond the reach of current RV or TTV) would inform the efficient prioritization of targets for follow-up observations, such as intensive RV campaigns or observations by JWST. The proposed work is relevant to the XRP call because it will improve our understanding of the chemical and physical processes of exoplanets (including their surfaces, interiors, and atmospheres) as well as the origins of their volatile envelopes.

John Monnier/University of Michigan
Long-Baseline Interferometry at the Exoplanet Frontier

The exoplanet field has remained vibrant and exciting due to the continuous development of new observing techniques and the refinement of older ones, both from the ground and from space. Here we propose to push the exoplanet frontier through the development of two different interferometric experiments that take advantage of the Michigan Infrared Combiner (MIRC) operating at the CHARA Array, a visible and near-infrared interferometer boasting the longest baselines and finest angular resolution in the world.

The main project will be to monitor a sample of hot-star binaries to search for astrometric wobble from orbiting giant planets -- Project ARMADA (ARrangement for Micro-Arcsecond Differential Astrometry). By narrowing our focus to binary systems, one of the stars can be used as a remarkable interferometric reference, enabling ultra-precise phase methods to measure gravitational perturbations by an orbiting giant planet. Our measurements will independently test the surprisingly claim for a 5x increase in giant planets around intermediate-mass stars (based on radial velocity data from evolved sub-giants, e.g., Bowler et al. 2010). While our interferometric method is limited to binary stars, we take advantage of this fact by crafting a binary sample to cover orbital separations from 1 to 100 AU, enabling us to directly see for the first time if giant planet formation is suppressed for intermediate-mass stars, extending recent Kepler work (e.g., Wang et al. 2014). For close binaries (separation only 10-20 milliarcseconds), we have already demonstrated <10 micro-arcsecond relative precision (comparable to the GAIA goal of 7 micro-arcsecond), sufficient to detect the astrometric wobble caused by massive planets around these stars.

A second experiment will attempt to measure the low-resolution spectra of molecular features in nearby non-transiting hot Jupiters at all phases of their orbits, crucial data needed to constrain the new generation of atmospheric circulation and chemical models. Despite the close orbits (about 0.05 AU) of hot Jupiters, CHARA is still able to resolve the separation between the host star and planet, permitting the use of precision closure phase methods to measure the star-planet separation and flux ratio. Once perfected, this technique can be applied to a range of nearby systems to measure orbits and to extract the planet spectrum and thermal phase curve, a feat heretofore only possible from space. An earlier attempt at this project resulted in upper limits of 1:2000 contrast (90% confidence) for one target (Zhao et al. 2011) and we demonstrate here that major new upgrades to our instrumentation have improved calibration and data throughput enough to justify a renewed attempt.

This work is directly relevant to NASA goals and specifically to the program element ``Exoplanet Research'' as we observationally address the goals to ``aid in the detection of new exoplanets'' and to ``understand the chemical and physical processes of exoplanets.'' In addition, the close involvement of theorists in our project will advance relevant program goals to theoretically understand the exoplanet atmospheres and the planet formation process by allowing a new comparison between exoplanet demographics of single and binary stars, and between solar-mass and higher mass stars. Our proposed research has direct relevance to NASA's Strategic Plan 2014, specifically Strategic Goal 1 (Expand the frontiers of knowledge, capability, and opportunity in space) and Objective 1.6 (Discover how the universe works, explore how it began and evolved, and search for life on planets around other stars).

Katie Morzinski/University of Arizona
Determining the optical-to-mid-infrared SEDs and empirical bolometric luminosities of young Jovian exoplanets via direct imaging with Magellan Adaptive Optics

Technical Background: Our team has built and commissioned an advanced adaptive optics (AO) system at the 6.5-m Magellan Clay telescope at Las Campanas Observatory, Chile. This system is called MagAO (PI Laird Close) and it uses an adaptive secondary mirror (ASM) with 585 actuators to apply the correction measured by its high-order pyramid wavefront sensor. Because we can correct at wavelengths as short as H-alpha, the MagAO system regularly produces the highest-spatial-resolution deep images to date. MagAO has been on-sky over 130 nights now and is in regular science operations at Magellan. The AO system is unique in having two science cameras operated simultaneously: the visible-light camera VisAO images the 550-1000 nm light, and the infrared camera Clio images the 1-5 micron light. Here we propose to use the MagAO system to characterize extrasolar giant planets (EGPs) discovered by GPI. GPI -- the Gemini Planet Imager (PI Bruce Macintosh) -- is a new high-order AO instrument at Gemini South (Macintosh et al. 2014), commissioned in 2014. In November 2014, the GPI science campaign began: The GPI Exoplanet Survey (GPIES; also PI B. Macintosh)

is an 890-hour survey to search 600 young nearby stars for EGPs over 3 years. GPI's integral field spectrograph can characterize planets from 0.95-2.4 microns. GPIES has already discovered a handful of planet candidates, and has just submitted our first paper about our first discovered exoplanet. MagAO is the only US facility in Chile that is capable of following-up GPI planets at a broader wavelength range from 0.55-5 microns. To improve the contrast of MagAO/Clio at 3-5 microns we have procured two new custom vAPP coronagraphs that enable high contrast at L and M bands. The goal of this project is to use MagAO/VisAO and MagAO/Clio to obtain full optical-to-mid-IR coverage of the SEDs of GPIES-discovered planets.

Theory Background: While H-band is ideal for the GPIES planet-search campaign, following up in the thermal IR is critical to better understand the properties of GPI-discovered planets. EGPs on wider orbits emit the bulk of their energy at 3-5 microns, and so it is crucial to observe these planets there to determine their bolometric luminosities and atmospheric properties such as non-equilibrium CH4-CO chemistry. Large errors in L_bol lead directly to large errors in inferred mass -- our mid-IR photometry will mitigate this issue. Because we are carrying out this program in coordination between the GPIES and MagAO teams, we have direct early-access to the GPI-discovered planets before they are made public -- hence we have a unique path for multiplying the GPI science value to the exoplanet community.

Proof-Of-Concept: Thus far, a few EGPs have been imaged at high contrast with both GPI and MagAO. Our canonical proofof-concept is beta Pictoris b which we observed with MagAO/VisAO in Ys (Males et al. 2014), MagAO/Clio in 3.1um, 3.3um, L', and M' (Morzinski et al. 2015), and with GPI in H (Macintosh et al. 2014). MagAO's 0.9-5 micron photometry with VisAO and Clio provides the first empirical determination of bolometric luminosity, and spans the blackbody peak to dually constrain mass and radius.

Proposed Project: This is an exciting opportunity to study the atmospheric properties and thermal evolution of young EGPs by fully measuring their spectral energy distributions. This program is well-aligned with the NASA Exoplanets Research Program's goals and will be carried out by experts uniquely situated at the intersection of the GPI and MagAO science and instrument teams. We require equipment, travel, and summer support for a total of only <$250k over 3 years. The timing to begin this project is ideal with the GPIES campaign having started in Nov. 2014 and already discovering its first planet, and with MagAO fully proven on-sky.

Julianne Moses/Space Science Institute
Atmospheric Chemistry and Aerosol Formation on Exoplanets

Objectives: The rapidly growing statistics for exoplanet properties such as radius, mass, bulk density, orbital period, and emission temperature reveal an amazing diversity of planetary properties beyond the narrow confines of our Solar System. Atmospheric characterization of these planets is proceeding at a slower pace, but observations to date

suggest that exoplanets possess highly diverse, often unexpected atmospheric properties. In this theory-based proposal, the team will investigate how different chemical processes act to control and modify the atmospheric composition of exoplanets with thick, deep atmospheres. The composition in turn affects how and where energy is deposited in the atmosphere, so studies of atmospheric chemistry provide an important framework from which to launch studies of atmospheric structure, energetics, and dynamics. The main goal of the proposed work is to further our understanding of the link between chemistry and aerosols in exoplanet atmospheres. Additional specific goals include a better understanding of the possible longitudinal variation of composition and aerosols on close-in, tidally locked exoplanets due to photochemistry, disequilibrium quenching, and aerosol condensation and evaporation as the hot, radical-rich dayside gas is transported to the cooler terminator and nightside regions and back to the dayside again. The theoretical models are motivated by recent observational evidence for clouds on extrasolar planets, for Rayleigh scattering signatures in exoplanet transit observations, and for unexplained orbital phase-curve behavior in exoplanet observations.

Methodology: Existing general circulation models (GCMs) will be used define the wind and temperature fields for exoplanets spanning a wide range of sizes and effective temperatures, such as GJ 1214b, GJ 436b, HD 189733b, WASP-43b, and WASP-12b. A thermochemical and photochemical kinetics and transport model will then be used to track the atmospheric chemistry and composition on these planets. Condensation, evaporation, gravitational settling, and other aerosol microphysical processes will be considered along with the gas-phase chemistry to track the production and loss of potential condensed phases. The GCMs predict that strong zonal winds will carry gas parcels across longitudes from the dayside to the nightside and back in a way that mimics diurnal variation of a rotating body. The derived zonal jets and longitudinally varying temperature profiles at low latitudes from the GCMs will be used to define this pseudo-rotation rate and "diurnal" thermal variation that will drive the time-variable chemistry as these gas parcels move across the planet. Model results will be used to create synthetic transit and eclipse spectra and phase-curve behavior that will then be compared to relevant observations of exoplanets.

Relevance: The proposed theoretical investigation seeks to advance our knowledge and understanding of the atmospheric chemistry, composition, and structure of extrasolar planets, all of which are broad objectives of the NASA Exoplanets Research Program. The work will help with the interpretation of exoplanet transit, eclipse, and phase-curve observations and will help place our own Solar System in a larger context of planetary formation within our galaxy.

Roman Rafikov/Institute for Advanced Study
Origin of exoplanets within and around binary stars

At least 20% of extrasolar planets are known to reside in binaries. Some of them, such as alpha Cen and gamma Cephei, are in small-separation binaries with semi-major axes less than 20 AU. In addition, several circumbinary planetary systems have been recently

discovered by the Kepler satellite. Understanding origin of such systems puts planet formation theories to a serious test, as planetary genesis in binaries involves many complications not present in the case of single stars. Strong dynamical excitation of planetesimals by the stellar companion, short lifetimes of protoplanetary disks - all these factors adversely affect planet formation in binaries. Recently, our group has reached progress in understanding of planetesimal dynamics in binaries and demonstrated, in particular, that gravity of protoplanetary disks plays a decisive role in the dynamics of planetesimals and their collisional outcomes.

Science goals and objectives

The proposed research will cover three main areas. Armed with our recent dynamical results, we will develop a complete picture of planetesimal accretion in binaries, addressing the origin of both circumstellar and circumbinary planetary systems. In addition, we will explore the physics of the gaseous component of protoplanetary disks in binaries with the goal of understanding their non-axisymmetric structure and evolution, as the latter strongly affects planetesimal dynamics. We will subsequently integrate these diverse pieces into a coherent picture of planet formation in binaries.

Methodology

Our study of planetesimal growth in binaries will include the following projects. We will explore the role of non-secular effects on planetesimal dynamics. These will include the possibility of evection resonance in systems with massive protoplanetary disks, effects of higher-m harmonics of the disk potential, perturbations due to the density waves excited by the companion in the disk. We will also study inclination evolution of planetesimals in disks which are misaligned with the binary orbit.

We will also explore protoplanetary disk physics in binaries. (1) We will build analytical understanding of eccentricity evolution of both circumstellar and circumbinary gaseous disks in binaries. (2) We will explore the effects of disk self-gravity on its eccentricity and precession. (3) We will calculate torques excited by the companion at the disk edge and apply our results to understand the truncation radii of the circumstellar and circumbinary disks. (4) We will investigate the back-reaction of the disk-binary coupling on the binary orbit, focusing on evolution of its eccentricity and semi-major axis. These tasks will include analytical investigation as well as the numerical verification using direct hydrodynamical simulations, for both circumstellar and circumbinary disks. Finally, using our understanding of planetesimal dynamics and disk properties we will develop detailed statistical, multi-zone models of planetesimal coagulation in binary stellar systems.

Relevance of the proposed research

Proposed research is directly relevant for the Exoplanets Research program. Among our goals are ``characterization of planets and planetary systems outside of our Solar System, including the determination of their compositions and dynamics". Our results will help to

``explain observations of exoplanetary systems, and improve understanding of the origins of exoplanetary systems." We hope that by carrying out this research we will be able to finally settle the fragmentation barrier issue and dramatically improve our understanding of planet formation in the extreme conditions of the binary stellar systems. This will also allow us to set important constraints on theories of planetesimal origin.

Dmitry Savransky/Cornell University
Enhanced Exoplanet Detection via Blind Source Separation

While indirect techniques including doppler spectroscopy and transit photometry have provided an incredible wealth of data on exoplanetary systems, direct imaging is necessary to cover the entire range of orbital separations, planetary masses and stellar ages. As the next generation of high-contrast instruments, including the Gemini Planet Imager and SPHERE, begin to perform large-scale imaging surveys, and as NASA begins planning for WFIRST-AFTA, which will include a coronagraphic instrument, it is becoming increasingly evident that post-processing will play a crucial role in the success of direct imaging studies.

Multiple different techniques have been developed to extract very faint planet signals from very noisy imaging data, and many of them, including principal component analysis (PCA) and singular value decomposition (SVD), are members of a general class of algorithms known as blind source separation (BSS). These algorithms all address the extraction of a specific signal from a mixture of noisy signals with limited knowledge of the signal sources and mixing processes. We propose a systematic investigation of BSS techniques for the extraction of exoplanet signals from imaging data sets and to quantify of errors associated with these extractions.

We are most interested in evaluating those BSS algorithms that have proven successful in other fields but have not yet been extensively investigated for exoplanet imaging. These include independent component analysis, which has only recently been applied to high resolution spectral exoplanet data, and common spatial pattern filtering, which has proven highly successful in multiple medical imaging applications, but has not yet been applied to astronomical data. In addition, stationary subspace analysis may prove highly useful when dealing with data sets containing quasi-static and rapidly varying noise terms along with the desired planetary signal. This describes many ground-based imaging data sets that contain slowly varying noise components due to instrument optics along with rapidly varying, possibly non-stationary noise components due to the atmosphere and the corrections of adaptive optics systems. We will implement each of these BSS sub-classes and test them, along with implementations of previously published PCA and SVD-based algorithms on a common data set composed of both synthetic data designed to mimic realistic imaging systems (with known input signals) as well as actual publicly available imaging data from multiple instruments.

This work directly addresses the Exoplanets Research program as it will aid in the detection of new exoplanets and may allow us to discover new exoplanet signals in

existing data from NASA assets (which occurred when PCA-based techniques were applied to Hubble data). The techniques and algorithms generated in this work can be used in processing data from multiple current and future NASA assets including the LBTI and the WFIRST-AFTA coronagraph. This work is also directly relevant to the goals of the Cosmic Origins programs as it will increase the number of known exoplanets and the quality of exoplanet data sets, thereby bringing us closer to understanding how the planets we see today were formed.

Evgenya Shkolnik/Lowell Observatory
VITALS: Vulnerabilities to Irradiation over Time of Atmospheres orbiting Low-mass Stars

We aim to quantify the high-energy radiation a planet around an M dwarf is exposed to throughout its lifetime in order to provide reliable input physics for irradiated planet models, and to make the first accurate predictions of the full UV spectral range which controls a planet's photochemistry and hydrodynamic escape. We will accomplish this by characterizing, and age-dating nearby young M stars of various masses, measuring their near- and far-UV (NUV, FUV) properties, and using these to build an empirically-guided grid of brand new upper-atmosphere M dwarf models, providing the best-possible inputs for exoplanetary photochemical models of a wide range of planet mass.

M dwarfs make up a full 75% of all the stars in the galaxy, and likely represent the most common and nearest hosts of all planetary systems. Yet our understanding of planet formation around such stars is the most uncertain around M dwarfs.

The stellar high-energy radiation of low-mass stars is a non-negligible fraction of the bolometric luminosity, depends strongly on stellar age, and controls much of a planetary atmosphere's photochemical evolution. How exactly does this high-energy radiation evolve with time? We will answer this question by first analyzing over 700 of the nearest and youngest low-mass stars we recently identified by age-dating each candidate using the most advanced techniques available (i.e. spectroscopic age diagnostics and kinematic matches to known young moving groups).

We have collected the necessary data using several of the world's biggest telescopes in both the northern and southern hemispheres, providing an in-hand and nearly all-sky spectroscopic survey of young M dwarfs, expanding the number of known such objects by a factor of 5. Our large repository of young M dwarfs with well-constrained ages will form the basis of the first comprehensive study of the UV history of a statistical sample of M stars, from 0.1 – 0.6 M_sun and from 10 Myr to several Gyrs old. We will analyze archived NUV and FUV photometry from GALEX surveys to produce the much-needed empirical constraints for M star upper-atmosphere models, as the current "photosphere-only" models grossly under-predict these fluxes. With these, we will make the first accurate predictions of the exceptionally damaging extreme-UV (EUV) emission as a function of stellar mass and age to study the evolution of exoplanetary atmospheric photochemisty for a wide range of planetary masses.

Relevance to NASA-Exoplanets Research: The proposed research directly addresses NASA's Exoplanets Research goals by (1) explaining observations of exoplanetary systems, i.e. the possible photoevaporation due to high stellar UV irradiation of close-in planets as the cause for the abundance of rocky planets orbiting M dwarfs, (2) improving our understanding of the origins of exoplanetary systems since the EUV to NUV spectral range is critical to the protoplanetary disk evolution, and (3) understanding the physical processes of exoplanets with respect to the photochemical evolution in the atmospheres of planets orbiting M dwarfs.

Ronald Walsworth/Harvard College Observatory
Reducing the Effect of Stellar Jitter to Enable RV Measurements of Earth-Like Exoplanets.

The next milestone in radial velocity (RV) measurements is the detection of Earth-like exoplanets: long-period, terrestrial worlds around solar-type stars. Reaching this milestone requires an order of magnitude improvement in RV precision to <10 cm/s. Primary challenges to reaching such RV precision include: (i) stable, long-term wavelength calibration of the astrophysical spectrograph; and (ii) characterizing and accounting for the effects of stellar "jitter." With previous NASA support, we met the first challenge by developing and successfully operating, with RV <10 cm/s precision, a visible wavelength laser-frequency-comb ("astro-comb") wavelength calibrator for the HARPS-N spectrograph, located at the Roque de los Muchachos Observatory in the Canary Islands. Here, we propose to develop techniques to remove the effects of stellar jitter by studying the Sun using an existing small, lowcost solar telescope and the HARPS-N spectrograph calibrated with the astro-comb. Our goal is the detection of Venus from its solar RV signature. Success would demonstrate the feasibility of RV confirmation and characterization of Earth-like exoplanet candidates identified by NASA's Transiting Exoplanet Survey Satellite (TESS) space mission and followed up by planned groundbased instruments such as G-CLEF.

The discovery and characterization of an Earth twin is of prime importance as stated in the 2010 A&A Decadal Survey. Results from the Kepler spacecraft demonstrate the possibility of finding Earth radius planets in the habitable zone. However, determining a dynamical mass for such worlds is critical for inferring their planetary nature. Although transit-timing variations and photo-dynamical analysis are promising techniques for determining a precise mass, TESS photometry will not have a sufficient baseline to observe them; only ground-based RV measurements will be able to determine the mass of TESS planets. Therefore, understanding the influence of stellar jitter on RV measurements is a key requirement for the characterization of an Earth twin and realizing the full scientific potential of TESS.

Much can be learned about stellar jitter by continuously monitoring a 'quiet' star such as the Sun with an ultra-high-precision RV instrument, in order to sample all the different timescales of perturbations. In particular, the stellar activity signal is semi-periodic

on a timescale of the rotational period of the star, typically tens of days, which makes it difficult to average away. However, given the 'time-pressure' for observations using ultra-precise spectrographs like HARPS-N, long-term continuous monitoring of the Sun is only possible if we observe during the day, which we propose to do using existing instruments: a small, low-cost solar telescope, which is currently operating and integrated with the HARPS-N spectrograph (providing state-of-the-art precision for RV measurements), with wavelength calibration (<10 cm/s long-term RV precision) provided by our operational astro-comb. Daily observations of the Sun will allow us to characterize all the sources of the stellar RV signal; and with the help of solar satellites (SOHO, SDO, SORCE), it will be possible (i) to understand from detailed imaging of the solar photosphere the photometry-RV correlation, and then (ii) to correct the observed RV signature for stellar signal variations. In particular, two hours of solar observations per day for two years will be sufficient to recover the RV signal induced by Venus on the Sun. Such a detection would be a convincing demonstration of the feasibility of detecting an Earth twin around a quiet, Sun-like star, using a sufficiently large telescope together with a state-of-the-art spectrograph and calibrator such as HARPS-N and the astro-comb.