# Exoplanet Demographics Conference
# November 9-13, 2020
# Tuesday Talk Abstracts

**Small Planets**

***Low-mass Exoplanet Demographics - Daniel Jontof-Hutter (Univ. of the Pacific)***

Exoplanet science is advancing rapidly on many fronts following the detection of thousands of planets, particularly from transit surveys. Precise stellar characterization has revealed the bimodal planetary size distribution, and has enabled precise planetary mass measurements with radial velocities and transit timing. Over 120 exoplanets less massive than 30 Earths have measured masses and radii (Jontof-Hutter, 2019, AREPS, 47, 141), and a remarkably diverse range of bulk densities among these exoplanets has been revealed. Planetary mass and radius characterization has also entered the terrestrial regime- over 30 exoplanets smaller than 1.6 Earth-radii have detected masses, and planets as small as Mars now populate the mass-radius diagram.

In this review, we summarize the progress that has been made in characterizing this diverse population: where planet sizes and incident fluxes inform on bulk planet properties, where compositions by volume are dominated by volatiles and where bulk planet properties within individuals systems differ substantially. To some extent, however, detection biases prevent individual characterizations from revealing underlying planet demographics. We review progress to correct for these biases in determining distributions of planet properties.

Looking forward, planetary system demographics will require observations to probe system architectures beyond the compact configurations that have been detected close to stellar hosts. A small number of compact multi-transiting systems show evidence of additional planets from radial velocities, and observing campaigns to detect non-transiting planets that orbit beyond the known planets have begun. In addition, dynamical modeling can characterize the parameter space in which additional planets are unlikely, and hence help inform the design of follow-up campaigns to focus observing time where there is discovery potential. Finally, as atmospheric characterization is set to flourish with JWST, and as new regimes of detectable exoplanet atmospheres await, we highlight a debiased sample of planets characterized with transit timing to explore atmospheric demographics.

***Sculpting the Close-in Planet Population Across the Main Sequence - Ryan Cloutier (Center for Astrophysics|Harvard & Smithsonian)***

One of the most important results in exoplanet demographics over the past half-decade has been the detection of the radius gap: the bimodality in the occurrence rate distribution of close-in planets smaller than Neptune. Both observations and models of planet formation and evolution agree that the radius gap arises from the existence of a transition from small terrestrial planets to larger non-rocky planets that host substantial gaseous envelopes. We are now tasked with trying to understand what physical process, or processes, are responsible for producing this rocky/non-rocky transition and whether these processes are universal across the entire main sequence. I will review the suite of physical processes proposed to explain the emergence of the radius gap, including photoevaporation, core-powered mass loss, and terrestrial planet formation in a gas-poor environment. I will focus on the unique model predictions of the gap's dependence on orbital separation, stellar mass, and age, as well as on how specific targeted observations can provide a clear pathway towards identifying the dominant physics at play. With the on-going TESS mission and the growing cohort of precision radial velocity spectrographs, the community is well-positioned to establish which processes are responsible for sculpting the radius gap around FGK stars, down to the lowest mass M dwarfs in the coming years.

***A Stellar Age Dependence of the Planet Radius Gap - Travis Berger (IfA, University of Hawaii)***

A major bottleneck for Kepler exoplanet demographics has been the lack of precise properties for most of the observed stars. In this talk, I will present the first homogeneous and precise characterization of all Kepler targets using Gaia DR2. Applying these improved stellar parameters to revise exoplanet properties, I will present the dependence of the planet radius gap on stellar mass and age for the full Kepler exoplanet sample and discuss implications for the competing theories of core-powered mass-loss and photoevaporation. In particular, I will present first evidence for the planet radius gap's dependence on stellar age on timescales of a Gyr, a result that is only predicted by core-powered mass-loss. In addition, I will show that low-flux sub-Neptunes appear to shrink on Gyr timescales, suggesting that most of these planets possess H/He envelopes that measurably contract over Gyr timescales as opposed to higher mean molecular weight atmospheres. Finally, I will reveal that there are bona-fide planets within the "hot sub-Neptunian desert" and show that these planets are preferentially orbiting more evolved stars compared to other planets at similar incident fluxes. The results detailed here demonstrate the potential for transformative characterization of stellar and exoplanet populations using Gaia data.

***Joint Mass-Radius-Period Distribution Modeling of Water Worlds - Andrew Neil (Univ. of Chicago)***

Water worlds have been hypothesized as an alternative to photo-evaporation in order to explain the gap in the radius distribution of Kepler exoplanets. We explore water worlds within the framework of a joint mass-radius-period distribution of planets. We employ hierarchical Bayesian modeling to create a range of mixture models that include multiple exoplanet populations. We model these populations - including planets with gaseous envelopes, evaporated rocky cores, evaporated icy cores, intrinsically rocky planets, and intrinsically icy planets - in different combinations in order to assess which combinations are most favored by the data. Using cross-validation, we evaluate the support for models that include planets with icy compositions compared to the support for models that do not. We further explore the population-level degeneracies between subpopulations of water worlds and planets with primordial envelopes. Looking forward, we demonstrate how to extend this analysis by incorporating planet interior structure models to directly model the composition distribution of exoplanets.

***Inferring "True" Small Planet Demographics with the Magellan-TESS Survey - MTS Team***

Recent results on the characterization of small planets have presented two questions: (1) Is there a range of super-Earth and/or sub-Neptune formation mechanisms? and (2) What is the precise and accurate planet mass-radius relation in the <4 Rearth regime? The Magellan-TESS Survey (MTS) is designed to address these two questions in a statistically robust, open framework that can connect observed planet distributions to true underlying populations. It will include masses (or mass limits), host star compositions, and system architectures of ~30 small TESS planets across a range of insolation fluxes. Its statistical robustness arises from quantifiable and uniformly applied choices for target selection and observation cadencing, a new feature compared to most previous transiting planet follow-up surveys. In this talk I will present the latest results from MTS, including our hierarchical Bayesian modeling of the mass-radius-insolation flux relation using our homogeneously-derived and bias-quantified sample.

## Giant Planets to Brown Dwarfs

### *Giant Planet Population Physics - Daniel Thorngren (University of Montreal)*

The study of giant planet physics was long limited to the four planets found in our solar system. However, giant exoplanet discoveries have enabled a powerful new approach to planetary physics: the statistical study of their populations. This work has only become possible recently, with a large sample of transiting planets with well-determined masses and radii. In this review, I discuss how through comparison with structure and evolution modelling, we can find insights that cannot be obtained from studies of the solar system. This includes new views on planetary composition, structural evolution, and atmospheric physics. I review recent and ongoing work regarding 1) the planetary mass-metallicity relation of giant planets, and how it does (or does not) connect with stellar metallicity, 2) the long-unsolved radius inflation problem of hot Jupiters, 3) how giant planets evolve over time in the face of brightening parent stars on and off the main sequence, and 4) the depth of the atmosphere's radiative-convective boundary, which affects interpretation of atmospheric spectra. I also discuss how this work connects with ongoing planet characterization efforts, prioritization of TESS target follow-up, planet formation studies, and connections to population studies of the physics of smaller planets.

### *The Obliquity Distribution of Ultra Hot Jupiters: A Population-wide View - Rafael Luque (Ins. de Astrofisica de Canarias)*

Ultra hot Jupiters (UHJs), which we define as gas giants with equilibrium temperatures above 2000 K, have recently emerged as a population of exoplanets with distinct atmospheric characteristics. The hottest of the hot Jupiters are amenable to extensive characterization due to their high temperatures, inflated radii, short periods, and atmospheres with large concentrations of atoms and ions relative to molecules exhibiting strong thermal inversions. The hosts are normally early-type, hot, rapidly rotating stars and their planets frequently reside in misaligned orbits. In this work, we carry out a homogeneous derivation of the obliquity of a sample of UHJs via the Rossiter-McLaughlin effect using new and archival high-resolution spectroscopic transit observations. We analyze the obliquity of the UHJ sample and study its dependence with the stellar parameters, orbital eccentricity, planetary mass, and atmospheric composition, comparing it with the larger population of hot Jupiters. UHJs show preferentially a wider range of obliquities, in agreement with the findings of Winn et al. (2010) that suggest that the photospheres of cool stars realign with the planet orbits due to tidal dissipation in their convective zones, while hot stars cannot realign because of their thinner convective zones.

### *The Eccentricity Distribution and Occurrence Rates of Warm, Large Exoplanets - Jiayin Dong (Penn State)*

Warm, Large Exoplanets (WaLEs) – defined here as planets larger than 6 Earth radii with orbital periods 8–200 days – are a key missing piece in our understanding of how planetary systems form and evolve. It is currently debated whether WaLEs form in situ, undergo disk or high eccentricity tidal migration, or even have a mixture of origin channels. These different classes of origin channels lead to different expectations for WaLEs' properties, such as their eccentricity distribution and occurrence rates. In this talk, I will first discuss our recent work where we uniformly search for WaLE candidates in the southern ecliptic hemisphere in the TESS Full Frame Images (FFIs) and discover a catalog of ~80 WaLE candidates. We characterize the eccentricity distribution of these WaLE candidates using hierarchical Bayesian models and find a two-population mixture model -- a low-e population for in situ or disk migration origins and a high-e population for high eccentricity tidal migration origin can well describe the observed WaLEs' eccentricities. Our hierarchical model suggests a mixture of origin channels and also an upper limit on the fraction of WaLE systems forming through high-eccentricity tidal migration. Furthermore, I will discuss our ongoing project on the validation of the WaLE candidates using ground-based telescopes and the TESS extended mission. By the end of the observation cycles, we aim to construct a well-understood WaLE catalog for a deeper understanding of WaLEs' eccentricity distribution and occurrence rates.

***Direct Imaging and Spectral Characterisation of Long Period Exoplanets and Brown Dwarfs - Emily Rickman (STScI)***

Very little is known about giant planets and brown dwarfs at an orbital separation great than 5 AU. And yet, these are important puzzle pieces needed for constraining the uncertainties that exist in giant planet formation and evolutionary models. Furthermore, evolutionary models of giant planets and brown dwarfs are plagued by a lack of observational constraints. The complex molecular chemistry of their atmospheres leaves a relatively wide parameter space for models to span.
To date, individual dynamical masses are known for only a handful of brown dwarfs, therefore any new detections contributes greatly to brown dwarf models as they provide important analogues for the characterisation of exoplanets. Radial-velocity measurements provide only a lower limit on the measured masses due to the unknown orbital inclination. Therefore, directly imaging these candidates is needed to break that degeneracy and provide constraints on the dynamical mass of the companion.

I have selected ideal targets for direct imaging using the radial-velocity CORALIE survey for southern extra-solar planets with over 20 years-worth of data containing a volume-limited sample of 1647 low-mass main sequence stars within 50 parsecs. As massive planets and brown dwarf companions are rare, one benefits from the CORALIE survey where we are able to identify golden targets for direct imaging. Detecting these giant companion candidates allows us to bridge the gap between radial-velocity-detected exoplanets and directly-imaged planets and brown dwarfs. I describe the progress towards the detection, characterisation and monitoring of widely-separated giant planets and brown dwarfs through both direct imaging and long-period radial-velocities. This includes the detection of several long-period radial-velocity giant planets and brown dwarfs, as well as the direct imaging of some of these companions with VLT/SPHERE and the discovery of a benchmark ~50MJup T-type brown dwarf. The discovery of such benchmark sources provides a powerful and critical tool of advanced evolutionary models.

As we move toward imaging smaller and smaller objects it is important to use these objects as a laboratory to test theoretical atmospheric models. The components of detecting long-period massive-companions helps to probe a parameter space in mass, separation and age where the occurrence rate of these objects is not well understood. They also serve as a stepping stone towards detecting smaller and smaller exoplanets using both of these methods of detection.

### *Towards the Underlying Composition Distribution of Exoplanets - Darin Ragozzine (Brigham Young University)*

What is the true underlying composition distribution of exoplanets and how does it vary as a function of orbital period, planetary system architecture, and stellar type? While the full answer to this question is yet to be revealed, it has profound implications for the formation and evolution of planetary systems. We will review many aspects of this question that have been addressed and their current limitations. In particular, we'll review the most up-to-date studies on biases in mass-determination techniques, demographics of Transit Timing Variations, observed mass-radius-period distributions, compositional inference from mass and radius, and how these relate to planetary architecture and stellar type. Our focus will be on the Kepler prime mission dataset -- the most powerful homogeneous survey for answering this question -- with comparisons to other detection and characterization methods. We identify a path forward to the underlying composition distribution using a combination of photodynamical modeling, occurrence rate corrections, and using the ensemble of planetary systems to infer population properties. We will share preliminary results of our research along this path toward the true underlying composition distribution.

### *On the Mass Distribution of Gas Giant Planets Forming Through the Core Accretion Paradigm - Fred Adams (Univ. of Michigan)*

This talk presents a theoretical framework for calculating the distribution of masses for gas giant planets forming via the core accretion paradigm. We present a collection of models for this mass distribution, with increasing complexity, for planets with masses in the range $0.1\mjup<M<10\mjup$. If the circumstellar disk lifetime is solely responsible for the end of planetary mass accretion, the observed (nearly) exponential distribution of disk lifetime imprints an exponential fall-off in the planetary mass function. This result is in apparent conflict with observations, which indicate that the mass distribution has a (nearly) power-law form $dF/dM \sim M^{-p}$, with index $p=1.3$, over the relevant mass range. The mass accretion rate onto the planet depends on the fraction of the (circumstellar) disk accretion flow that enters the Hill sphere, and on the efficiency with which the planet captures the incoming material. Models for the planetary mass function that include distributions for these efficiencies, with uninformed priors, can produce nearly power-law behavior, consistent with current observations. The disk lifetimes, accretion rates, and other input parameters depend on the mass of the host star. We show how these variations lead to different forms for the planetary mass function for different stellar masses. Compared to stars with masses $M_\ast=0.5-2M_\odot$, stars with both smaller and larger masses are predicted to have a steeper planetary mass function (fewer large planets). However, the distribution of mass ratios $q = M/M_\ast$ is more universal than the planetary mass function itself.

### *Heavy-Metal Jupiters by Major Mergers - Sivan Ginzburg (UC Berkeley)*

Some extrasolar Jupiters have large metal masses, well above the mass needed in a solid core to trigger runaway gas accretion. We demonstrate that such “heavy-metal Jupiters” can result from planetary mergers. We provide a simple derivation of the mass-metallicity relation for giants, and compare to observations. While the average gas giant merges about once to double its core, others may merge multiple times as merger trees grow chaotically. Chaotic collisional histories naturally reproduce the large scatter in observed giant planet metallicities. Mergers potentially correlate metallicity, eccentricity, and spin.

***Exploring the Transition Between Giant Planets and Brown Dwarfs with TESS and Gaia - Theron Carmichael (Harvard Univ.)***

Traditionally, astronomers have separated giant planets from brown dwarfs based on the object's mass. Specifically, objects more massive than 13 Jupiter masses but less massive than 80 Jupiter masses are considered to be brown dwarfs. However, in detail, the lower mass threshold is 11 to 16 Jupiter masses depending on the metallicity of the object. This betrays how arbitrary a purely mass-based distinction between planets and brown dwarfs is. Instead, we must take a critical look at the population of brown dwarfs for which we have the most fundamental information: transiting brown dwarfs. Transiting brown dwarfs are rare, yet they provide us their mass, radius, and age. These are the most fundamental properties for any celestial object, and for transiting brown dwarfs they allow us to directly test substellar evolutionary models. These models describe the internal structure of brown dwarfs, explain how and why brown dwarfs contract with age, and aim to describe brown dwarf formation as it differs from that of planets and stars. To test these models directly, we compare them to observed masses, radii, and ages of transiting brown dwarfs. Through a better understanding of how well these models describe the population of transiting brown dwarfs, we will develop a better definition of what truly makes a brown dwarf different than a giant planet: its formation mechanism. It is certainly true that in the mass range spanning between giant planets and low-mass stars that the dominant formation mechanism must change in a significant way. If we can determine which point---or distribution of points---that this change occurs, then we will have a more physical way to distinguish planets from brown dwarfs. In this talk, we will examine the transiting brown dwarf population in an effort to understand three things: 1) how the TESS and Gaia missions have enhanced our understanding of the masses, radii, and ages of transiting brown dwarfs,  2) how the mass, radius, and age of transiting brown dwarfs are used to test substellar isochrones, 3) how the transiting brown dwarf population can help create a distinction between planets and brown dwarfs based on a change in formation mechanism.