Exoplanet Demographics Conference
November 9-13, 2020
Monday Talk Abstracts

History of Exoplanet Demographics

The History of Exoplanet Demographics: Observation and Theory - Scott Gaudi (The Ohio State University) and Ruth Murray-Clay (UCSC)

Inner Planetary System Demographics

The Kepler Transiting Exoplanet Sample: Physical Properties - Jason Rowe (Bishop's University)

The 4-year Kepler Mission has discovered at least 4300 validated exoplanets and exoplanet candidates. Measuring reliable, repeatable and trustworthy physical properties and the orbital environment of these planets is fundamental towards understanding the underlying demographics. Fundamental properties include planetary radius, orbital period, orbital inclination, incident flux, eccentricity and transit-timing-variations (TTVs). Reliable posterior distributions require assessment of the underlying stellar parameters and the applied methodology to model a planetary transit in the presence of instrumental and astrophysical noise. This talk will review the evolution of planetary properties from the Kepler sample beginning with the first Kepler-Object-of-Interest (KOI) catalogues (Borucki, et al 2011) through subsequent major data releases including Q6, Q8, Q12, DR24, DR25 and recent work based on state-of-the-art noise models and significant improvements in stellar priors now available from the astrometric GAIA mission and ground-based spectroscopic follow-up. The complication of a non-uniform stellar disk, integrated disk stellar variability and non-Gaussian instrumental artifacts such as readout cross-talk affects extracted parameters and introduces potential biases impacting inferred physical properties such as planet radius and recovery statistics such as signal-to-noise. Methods to fit transit models to observations and recover posteriors can bias reported distributions, such as orbital inclination. The assessment and inclusion of TTVs improves precision of mean-orbital periods and precision transit shape measurements. In the short decade since the first Kepler planet physical properties were published the field has seen a transformational change in our approach to transit modelling and have led to a new uniform reduction of the Kepler sample. A new Kepler properties catalogue will be presented that takes into account our best knowledge of stellar parameters and best transit model methodologies.

Forward Modeling the Distribution of Intrinsic Architectures of Inner Planetary Systems - Eric Ford (Penn State)

I propose to review recent progress in characterizing the intrinsic distribution of inner planetary architectures (P <~ 1 year) based primarily on observations from NASA's Kepler mission. I will draw from over a dozen papers to compare and contrast results for the number of planets per inner planetary system, the relationship of planet sizes and orbital periods within a system, potential causes of the apparent "Kepler dichotomy" and "peas-in-a-pod" phenomena, and the putative correlations of eccentricities and/or inclinations with multiplicity. Then, I will summarize how forward modeling of both the intrinsic population and selection effects has improved our understanding of each of the above issues, along with the implications for planet formation theory. I will discuss the current limits of our knowledge of the distribution of inner planetary architectures due to degeneracies from using solely transit observations and/or the size of the Kepler sample. Finally, I will describe how precision radial velocity surveys can test state-of-the-art population models by detecting and characterizing non-transiting planets.

Detection Limits and Occurrence Rates of the CARMENES M Dwarf Survey - Silvia Sabotta (Thuringian State Observatory)

The CARMENES radial velocity survey is one of the most extensive radial velocity surveys for M dwarfs. It has has been monitoring a sample of more than 300 low-mass stars for more than 4 years and discovered more than 30 exoplanets. This data set holds a treasure for planet demographics studies that waits to be uncovered. As the survey is still ongoing, we present our analysis of a subset of 125 stars that we stopped observing for various reasons. In my talk, I will present a statistical analysis of the past survey and show how we identified and corrected for various biases.
The planetary occurrence rates we derived provide important clues for our understanding of the formation mechanisms of planetary systems around low-mass stars.

The Typical Planets Discovered by Transit Surveys and Their Implications for Planet Formation and Evolution - Kevin Schlaufman (Johns Hopkins University)

All mass--radius relations for low-mass planets published to date have been affected by observational biases. Since planet occurrence and primordial atmospheric retention probability increase with period, the ``typical'' planets discovered by transit surveys may bear little resemblance to the short-period planets sculpted by atmospheric escape ordinarily used to calibrate mass--radius relations. An occurrence-weighted mass--radius relation for the typical low-mass planets in the Galaxy observed so far by transit surveys requires both typical Earth-mass and Neptune-mass planets to have a few percent of their mass in H/He atmospheres to explain their observed radii. Unlike the terrestrial planets in our own solar system that finished forming long after the protosolar nebula was dissipated, these Earth-mass planets discovered in transit surveys must have formed early in their systems' histories. The existence of significant H/He atmospheres around Earth-mass planets confirms an important prediction of the core-accretion model of planet formation. It also implies that such planets can retain their primordial atmospheres and requires an order-of-magnitude reduction in the fraction of incident XUV flux converted into work usually assumed in photo-evaporation models. In contrast to Uranus and Neptune, which have at least 10% of their mass in H/He atmospheres, the typical Neptune-mass planets discovered in transit surveys are H/He poor. The implication is that they must have formed in much hotter parts of their parent protoplanetary disks than Uranus and Neptune's formation location in the protosolar nebula.

A Uniform Sample of K2 Planets and Early Occurrence Results - Jon Zink (UCLA)

Up to this point the Kepler mission data has been considered the gold standard for exoplanet occurrence rates. However, 18 campaigns of data, sampling a variety of Galactic latitudes, were collected following the malfunction that lead to the end of the Kepler prime mission. These fields provide a unique opportunity to understand how exoplanet occurrence is affected by Galactic latitude, stellar metallicity, and stellar age. With a fully automated pipeline now able to detect and vet transit signals in K2 data, we can measure the sample completeness and reliability. Doing so, we present the first uniform analysis of small transiting exoplanet occurrence outside of the Kepler field and find the FGK samples are relatively consistent. This early result also provides supporting evidence for metallicity driven planet formation. With all of the campaigns now fully processed, we will make public the occurrence rate tools needed to analyze this new rich dataset.

Outer Planetary System Demographics

Planet Demographics from the Outside-in: Properties of Long-period Giant Planets from Direct Imaging Surveys - Brendan Bowler (The University of Texas at Austin)

Direct imaging is sensitive to the outskirts of young planetary systems. About 15 substantial high-contrast imaging surveys have been completed in as many years, including recent results from second-generation instruments with extreme adaptive optics capabilities. Despite the low intrinsic occurrence rate of giant planets between 10-100 AU, these campaigns have now amassed large enough samples to tease out correlations between planet frequency and other parameters such as stellar host mass and presence of a debris disk. Additionally, the ensemble of discoveries are providing the statistical leverage to constrain how long-period planets are distributed in mass and separation. In this review I will provide an overview of giant planet demographics uncovered by direct imaging surveys, including both the implications and limitations of these measurements. I will also highlight the connection of imaged planets with those flanking this population at closer separations (from long-baseline radial velocity programs) and at much wider separations (from seeing-limited infrared surveys). Altogether these results are jointly helping to constrain the demographics of giant planets spanning five decades in orbital distance.

Testing the Core Accretion Theory with Exoplanet Demographics from Microlensing and Radial Velocities - David Bennett (NASA GSFC/Univ. of Maryland)

The formation of planets beyond the snow line is an important aspect of the core accretion theory. While the snow line is well beyond the habitable zone, it is thought that the planet population beyond the snow line can influence the habitability of planets by controlling delivery of volatiles, such as water, to planets in the habitable zone. However, these planets are largely undetectable by the transit method. The microlensing method has the highest sensitivity to low-mass planets beyond the snow line, while the radial velocity method is sensitive to giant planets over a wide range of orbital separations. I present a joint Bayesian analysis of microlensing and radial velocity demographics studies to investigate the demographics of wide-orbit planets. This includes an investigation of what role, if any, the runaway gas accretion process has on the final distribution of planets beyond the snow line.

Cold Planet Demographics from 12 years MOA-II Microlensing Survey Data - Daisuke Suzuki (Osaka University)

The Microlensing Observations in Astrophysics (MOA) collaboration has been conducting a high cadence microlensing survey toward the Galactic bulge since 2006 by using a dedicated 1.8m MOA-II telescope in New Zealand. They find 5-10 microlensing planets per year with other microlensing survey / follow-up teams. Previously, we derived a planetary mass-ratio function from the 6yrs MOA-II microlensing survey data in 2007 – 2012 including 23 planets and found a break around the mass-ratio of 0.0001, instead of single power law mass-ratio function used before (Suzuki et al. 2016). However, the slope of the mass-ratio function for the planets with mass-ratio below the break are not well determined because the planets sample below the break was not large enough. We extend this study by using another set of 6yrs survey data in 2013 – 2018. The expected number of planets in the total sample is roughly 50. In this talk, we will show the preliminary result for the updated mass-ratio function for cold planets, as well as the dependency on the separation (projected star-planet distance normalized by the Einstein radius). Also, we will briefly introduce the PRIME project that is expected to start the first dedicated NIR microlensing survey in 2021, as a precursor of the microlensing survey by Roman Space Telescope.

The Gemini Planet Imager Exoplanet Survey: Giant Planet and Brown Dwarf Demographics from -100 AU - Eric Nielsen (New Mexico State University)

The Gemini Planet Imager Exoplanet Survey (GPIES) has observed 521 young, nearby stars, making it one of the largest, deepest direct imaging surveys for giant planets ever conducted. With detections of six planets and four brown dwarfs, including the new discoveries of 51 Eridani b and HR 2562 B, GPIES also has a significantly higher planet detection rate than any published imaging survey. Our analysis of the uniform sample of the first 300 stars reveals new properties of giant planets (>2 MJup) from 3-100 AU. We find at >3 sigma confidence that these planets are more common around high-mass stars (>1.5 solar masses) than lower-mass stars. We also present evidence that giant planets and brown dwarfs obey different mass functions and semi-major axis distributions. Our direct imaging data imply that the giant planet occurrence rate declines with semi-major axis beyond 10 AU, a trend opposite to that found by radial velocity surveys inside of 10 AU; taken together, the giant planet occurrence rate appears to peak at 3-10 AU. All of these trends point to wide-separation giant planets forming by core/pebble accretion, and brown dwarfs forming by gravitational instability.

The Demographics of Young Giant Exoplanets Below 300 AU from the SPHERE Infrared Survey for Exoplanets (SHINE) - Arthur Vigan (CNRS /LAM)

The SPHERE infrared exoplanet (SHINE) project is a 500-star survey performed with VLT/SPHERE for the purpose of directly detecting new sub-stellar companions and understand their formation and early evolution. We present the results of a first statistical analysis for a sub-sample of 150 stars spanning spectral types from B to M, representative of the full SHINE sample, which constrain the frequency of sub-stellar companions with masses between 1 and 75 MJup and semi-major axes between 5 and 300 au. Based on the detection limits obtained for each star and the 13 detections in the sample, we use a Markov chain Monte Carlo analysis to compare our observations to (1) a parametric model based on observational constraints, and (2) numerical models that combines state-of-the-art core accretion and gravitational instability planet population synthesis. Using our parametric model, we derive the frequency of sub-stellar companions around BA, FGK and M stars and we demonstrate that a planet-like formation pathway probably dominates the mass range from 1 to 75 MJup for companions around BA stars, while for M dwarfs brown dwarf binaries dominate detections. Using our population model, and restricting our sample to FGK stars, we derive a frequency that is consistent with the parametric model and we show that qualitatively, the contribution of the core accretion part of the model seems enhanced over the gravitational instability part. Finally, we conclude with the implications of our results in the broader context of giant planet formation theory.

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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.

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Wednesday Talk Abstracts

Architectures of Systems: Observations

What We Learn from Multi-planet Systems - Wei Zhu (Canadian Institute for Theoretical Astrophysics)

Multi-planet systems contain rich information about the formation and evolution history of planetary systems. For example. The existence and the properties of additional planets can be used to distinguish planet formation theories, and the mutual inclination and the spacing between planets provide constraints on the dynamical evolution of the system as a whole. Multi-planet systems are also the key to link different detection techniques. In this talk, I will first discuss the challenges and current status in taking planet multiplicity into the statistical analysis. I will then review our current understanding about the demographics in terms of the multi-planet system architecture, specifically the correlation between different planet populations and the relative properties (e.g., size & mass) of planets around the same host. A discussion of theoretical implications and open issues will also be provided. Finally, I will briefly discuss the pathways to combine results from ongoing and upcoming missions such as TESS, Gaia, and WFIRST. Results from these different missions (and thus different techniques) can be combined through multi-planet systems to provide much more information than what they can individually.

Demographics of Multi-Planet Systems - Lauren Weiss (University of Hawaii at Manoa)

What can the architectures of planetary systems teach us about the dominant planet formation, migration, and evolution pathways? Multi-planet systems are natural laboratories in which planets form around the same star and within the same protoplanetary disk, offering a controlled environment for studying planet formation. With 400 multi-planet systems hosting at least 1000 planets already discovered, we can study the demographics of multi-planet systems. I will review the demographics of planet orbits, masses, and compositions in multi-planet systems, and more importantly, the demographics of how planets are related to their planetary siblings in each of these properties.

Architecture and Dynamics of Kepler's Multi-Transiting Planet Systems: Comprehensive Investigation Using All Four Years of Kepler Mission Data - Jack Lissauer (NASA Ames)

This talk will report results from a soon to be completed study by our group that expands upon our previous analyses presented in Lissauer et al. (2011, ApJS 197, 8) and Fabrycky et al. (2014, ApJ 790, 146). The Kepler data set now includes ~ 700 multiple-planet systems, far more than were available for our previous two studies, and they provide a powerful means to study the statistical properties of planetary systems. The increased numbers and better information about planetary radii and the properties of stellar hosts allow more statistically-robust analyses of the entire ensemble of Kepler multis and also independent analyses of subsets of the population. Early in the mission it was shown that Kepler was finding very few giant planets in systems with more than one transiting planet (Latham et al. 2011, ApJL 732, 24). With the full data set in hand, it is now apparent that unaccompanied planets (singles) and planets in multi-planet systems (multis) have the same size distributions throughout the range 0.5 - 3 R_Earth and also throughout the range 5 - 12 R_Earth; however, multis are about three times as abundant relative to singles in the smaller size range as in the larger one. This result argues that low-mass gas-rich planets, which dominate the size range 5 - 8 R_Earth, are more akin to the jovian planets that are tens to hundreds of times as massive than they are to the super-Earths and sub-Neptunes that have masses similar to their own. We reinforce our previous findings that most pairs of planets within the same systems are neither in nor near resonances and that there is a strong excess of planets having period ratios slightly larger than those of first-order mean-motion resonances. However, neglecting a few systems whose planets are locked in 3-body resonances, the deficit of planet pairs with period ratios just narrow of resonance is as large as the excess of planets wide of resonance within root N statistical uncertainties, suggesting that there is no overall excess of planet pairs in the vicinity of resonance. This result contrasts with predictions from planet migration models and radial velocity observations that find orbital resonances among planets (which typically have longer periods and are more massive than the bulk of Kepler planets) are common. We find that three-body resonances among planets are also uncommon, and those that are present are usually associated with two-body resonances or near-resonances.

Cold and Low-mass: Occurrence Rate of Extrasolar Ice Giants - Radek Poleski (Univ. of Warsaw)

Exoplanet analogs of Solar System ice giants, Uranus and Neptune, are extremely hard to discover due to long orbital periods and low intrinsic luminosities. Formation of Uranus and Neptune poses a problem to planet formation models due to the low density of protoplanetary discs at large radii and too short disc lifetimes. We can gain more understanding of Uranus and Neptune formation from their exoplanet analogs. Such exoplanets were already found using the gravitational microlensing technique. The sensitivity of the microlensing technique does depend on the planet-to-star mass ratio and planet position and not on either orbital period or planet luminosity. I will present occurrence rate of the wide-orbit microlensing planets derived based on known planets and planet detection efficiency from most recent microlensing data.

Frequency and Properties of Free-floating Planets - Przemek Mroz (Caltech)

Thousands of extrasolar planets have been discovered up to date. Although many of the known exoplanets do not resemble those in our Solar System, they have one thing in common - they all orbit a star. However, theories of planet formation and evolution predict the existence of free-floating planets, gravitationally unattached to any star. They may form as a result of dynamical processes in young planetary systems or during late stages of host star evolution.

Gravitational microlensing is uniquely suited for finding free-floating planets. I will present the current constraints on the frequency and properties of rogue planets in the Milky Way based on long-term observations of microlensing events in the Galactic bulge by the OGLE sky survey. I will also present several of the most promising candidate free-floating planets discovered to date. Finally, I will briefly discuss the future prospects for determining the frequency and mass function of rogue planets by the planned microlensing experiments.

Architectures of Systems: Theory

Using Radius-dependent Occurrence Rate Profile to Reveal Formation Pathways - Eve Lee (McGill University)

One of the long-standing issues in exoplanet science is identifying the formation location of planets; in particular, whether most planets have undergone a long-range migration or a largely in situ formation. In this talk, I will review how the distributions of orbital periods (planet occurrence rate vs. orbital period) and period ratios can be analyzed to reveal the formation pathways of exoplanets. Why is the occurrence rate of sub-Neptunes flat in log orbital period (unlike their larger counterparts)? How do we understand its fall-off inside ~10 days? How much migration is required to account for the excess of planet pairs just outside of first order mean motion resonances? I will also discuss how the shape of the period distribution changes with planet radii, and how we may leverage this radius-dependent difference to probe potentially diverse arrays of formation pathways that shape the observed diversity of exoplanets.

A Compositional Link Between Warm Super-Earths and Cold Jupiters - Martin Schlecker (MPIA)

Recent demographic studies have suggested a positive correlation between the occurrence rates of inner super-Earths and outer giant planets, challenging some established planet formation theories. Using global simulations that model the evolution of a protoplanetary disk and planetary growth via core accretion, we have produced a synthetic population of 1000 multi-planet systems that qualitatively confirms this observation.

A peculiar trend emerges when we associate the disk initial conditions with the bulk composition of the resulting planets: in disks of moderate solid content (~100 Mearth), super-Earths form from icy material beyond the water ice line and migrate to observable distances. No giant planets are formed. On the other hand, in massive disks (~>200 Mearth), dry super-Earths form on close orbits and are frequently accompanied by an outer gas giant. This results in the testable hypothesis that high-density inner super-Earths are proxies for cold Jupiters in the same system. I will discuss how a confirmation of this prediction would constrain central open questions in contemporary planet formation theory, ranging from efficiency of pebble accretion to planet migration behavior.

Can Large-Scale Migration Explain the Giant Planet Occurrence Rate? - Tim Hallat (McGill)

Jupiters and sub-Saturns share a similar shape of distributions in orbital periods, which may hint at a common formation pathway. In this work we assess whether the observed occurrence rate vs. orbital period can be explained by large-scale migration using self-consistent calculations of planetary envelope growth and planet-disk interaction. We demonstrate that disk-induced migration cannot simultaneously explain the observed distribution of orbital periods and masses of gas giants inside ~300 days. While the overall rise in the number of giants at longer orbital periods requires systematically more massive giants farther from the star, such a trend is not observed. We further show that the migration paradigm predicts the sub-Saturn occurrence rate to be flat in log orbital period, inconsistent with that observed. Our results suggest that large-scale migration is not the general origin of Jupiters and sub-Saturns.

Sub-Neptune Formation: The View from Resonant Planets - Nick Choksi (UC Berkeley)

While most pairs of sub-Neptunes are not in mean-motion resonance, some are. We examine the non-resonant and 3:2 and 2:1 resonant populations and show how their orbital period distributions faithfully record how sub-Neptunes interacted with each other, their parent circumstellar disk, and their host star. Orbits are sculpted mainly by disk dynamical friction which damps eccentricities and drives migration. The interplay between dynamical friction and resonant forcing decides conclusively how sub-Neptunes completed their formation: whether in a gas-rich disk (e.g., by pebble accretion) or in a gas-poor disk (e.g., by giant impacts). We also show that the resonances established during the last doublings in planet mass are stable, contrary to an earlier claim.

The Origins of Multi-Planet Systems with Misaligned, Nearby Companions - Juliette Becker (Caltech)

Ultra-short period planets provide a look at the inner edge of the allowed parameter space for planetary orbits. One particularly intriguing geometry of system containing ultra-short period planets is high multiplicity systems where the ultra-short period planet and the outer planets exist in two different dynamical states. This has manifested in the observational data as a small number of stars hosting systems of tightly packed coplanar inner planets as well as an ultra-short period planet, where the orbit of the latter is misaligned relative to the mutual plane of the former. We describe two different mechanisms that can produce an ultra-short period planet that is misaligned with the rest of its compact planetary system: natural decoupling between the inner and outer system via the stellar quadrupole moment, and decoupling forced by an external companion with fine-tuned orbital parameters. These two processes operate at different timescales, and can thus occur simultaneously or independently within a single system. We use the K2-266 system as an example to illustrate the dynamics of these two processes. We will also discuss the possibility of placing constraints on when ultra-short period planets in multi-planet systems arrive at their final orbital locations using the results of this work.

Architecture of Systems: The Role of Giant Planet Migration on the Formation of Systems with Multiple Rocky Planets and Super-Earths - Nader Haghighipour (IfA, Univ. of Hawaii)

We report the results of a major initiative on understanding the role of giant planet migration on the formation and orbital architecture of systems with super-Earths and terrestrial-class bodies. The goal of our project is to determine the connection between the type, number, and rate of the migration of giant planet(s) and the mass, frequency, size distribution, and orbital assembly of the final super-Earths and rocky bodies. We have carried out several hundred simulations for different values of the mass and migration rates of giant planet(s), different mass distribution and surface density profile of the protoplanetary disk, and different masses of the central star. Results indicate that, as expected, multiple rocky planets and small super-Earths form in systems where giant planet migration terminates at distances away from the central star interior to which the protoplanetary disk can maintain its material to accommodate planet formation. Capture into resonance of migrating giant planets does not play a significant role as long as the increased influence zones of these planets still allows the protoplanetaty disk to maintain planet forming material. Our simulations indicate that chain-resonance small, rocky bodies are results of the migration of planetary embryos, and close-in large super-Earths (mini-Neptunes) are the failed cores of giant planets that migrated out of their birthplaces. We discuss details of our simulations and present an analysis of the frequency of rocky planets and super-Earths in multi-planet systems in comparison to the outcome of planet formation models in our solar system and some of the extrasolar planets.

Self-Consistent Planet Populations for Direct Imaging Space Missions - Shannon Dulz (Univ. of Notre Dame)

We have developed a suite of numerical models to determine the extent to which ground-based observing programs could improve the planet characterization efficiency of flagship direct imaging missions. As a first step in the process, we have developed tools that may be used to synthesize exoplanet populations based on the occurrence rates from multiple detection methods (transit, RV, imaging). We find that naive extrapolation of planet occurrence from small to large semimajor axes (tens of astronomical units) leads to an unrealistically high number of cold planets, particularly Neptune-mass planets that result in unstable orbits. As a solution, we impose stability criteria based on mutual Hill radii. In this presentation, we show that dynamically packed systems may be used as a limiting case to assess the occurrence rates of imageable planets on the outskirts of their solar systems. Through these synthetic populations, our research quantifies the gains in mission efficiency due to a precursor RV survey. The results will have important implications for planned space missions such as the Roman Space Telescope, LUVOIR, and HabEx.

The Intrinsic Architectures of Planetary Systems: Correlations of AMD-Stable Systems - Matthias He (Penn State)

Kepler's multi-transiting planet systems provide valuable insights into the correlations within planetary systems and their architectures if the detection biases are properly accounted for. In He, Ford, & Ragozzine (2019, 2020), we used SysSim to forward model the Kepler catalog and showed that planets in the same system are more similar in period and in size than if they were drawn independently, the fraction of stars with planets (with Rp>0.5R_Earth and 3d<P<300d) increases towards later type (cooler) stars, and the observed multiplicity distribution can be well matched by two populations consisting of a low and a high mutual inclination component (a Kepler dichotomy). Here, I will present a new model to show that a broad, multiplicity-dependent distribution of eccentricities and mutual inclinations arising from systems at the angular momentum deficit (AMD) stability limit can also reproduce the observed population. Systems with intrinsically more planets have lower eccentricities and mutual inclinations. For each intrinsic multiplicity count, the distributions of eccentricities and mutual inclinations are close to lognormal, instead of the previously assumed Rayleigh distributions. This trend with multiplicity arises from the dependence of the critical AMD on the minimum period ratio in the system, as systems with tightly-spaced planets must have low AMD in order to remain stable. We also find that intrinsic single planets have higher eccentricities than multi-planet systems. I will show that there is evidence for these trends with multiplicity in the Kepler distributions of circular-normalized transit durations and transit duration ratios. Altogether, our new model demonstrates that a single population of AMD-stable planetary systems can match the observed population, eliminating the need for a dichotomy in either multiplicity or mutual inclinations. I will also revisit the observed "peas in a pod" trends and show that the preferences for the ordering of planets in increasing size and for their uniform spacings cannot be explained by detection biases, and are even more extreme than our simple clustering in periods and planet sizes. Finally, I will discuss how our simulated planet catalogs can be used to inform RV follow-up efforts in the search for additional non-transiting companions in systems with transiting planets (such as those observed from the TESS mission).

Exoplanet Demographics Conference
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Thursday Talk Abstracts

Exoplanet Demographics with Stellar Properties

A Review of the Exoplanet-Host Star Composition Connection - Johanna Teske (Carnegie)

For most exoplanets, we will never observe them directly but only infer their properties based on observations of their host stars. High resolution spectroscopy has given us an important window into the compositions of exoplanets through host star chemical abundances. We think host star abundances to some extent are like ``genes'' passed on to their orbiting planets, and thus provide insight into the building blocks that went into forming planets. Host star abundances have also been used to infer likely evolution pathways in different categories of exoplanets. From the first giant exoplanet detections, to the current era of bulk density characterization, and looking toward the upcoming era atmospheric characterization, host star abundances have and will continue to be an important ingredient to understanding exoplanet demographics. In this talk, I will present a brief review of what we have learned thus far about the connection between host star and exoplanet composition, and what new information/techniques in this subfield will help make progress in discerning underlying planet formation pathways.

How Common is Planet Engulfment? - Aida Behmard (Caltech)

Dynamical evolution can cause planets to be engulfed by their host stars. Following engulfment, the stellar photosphere abundance pattern will reflect accretion of rocky material that composes planetary cores by exhibiting refractory enhancements in order of condensation temperature. Multi-star systems are excellent environments to search for such abundance trends because these stars share the same natal gas cloud and primordial chemical compositions to within 0.05 dex. Thus, refractory differences above 0.05 dex that trend with condensation temperature between stellar companions constitute a signpost of planet engulfment. Such observations have been carried out for a few systems, and have occasionally yielded robust engulfment signatures, e.g., Kronos and Krios (Oh et al. 2018), but only a handful targeted systems with known planets. We aim to augment this sample by carrying out a survey using Keck-HIRES of 40 multi-star systems where one star is known to host a planet. The sample of planets hosted by these systems is diverse and includes hot Jupiters, close-in multi-planet systems, and gas giants at a range of orbital periods. Using the Spectroscopy Made Easy tool, we have obtained abundance patterns for each system that can be assessed for possible engulfment signatures. We will present preliminary results from this survey, which will ultimately be used to constrain the prevalence of planet engulfment, examine its role in shaping current planetary system architectures, and investigate possible engulfment-related patterns in stellar and planetary properties.

The California-Kepler Survey: Revisiting the Minimum-Mass Extrasolar Nebula with Precise Stellar Parameters - Fei Dai (Caltech)

We investigate a possible correlation between the solid surface density Σ of the minimum-mass extrasolar nebulae (MMEN) and the host star mass $M_\star$ and metallicity [Fe/H]. Leveraging on the precise host star properties from the California-{\it Kepler}-Survey (CKS), we found that Σ= 50^{+33}_{-20} \rm{~g~cm}^{-2} (a/1AU)−1.75±0.07 (M⋆/M⨀)1.04±0.22 100.22±0.05[Fe/H] for {\it Kepler}-like systems (1-4R⨁; a<1AU). The strong $M_\star$ dependence is reminiscent of previous dust continuum results that the solid disk mass scales with $M_\star$. The weaker [Fe/H] dependence shows that sub-Neptune planets, unlike giant planets, form readily in lower-metallicity environment. The innermost region (a<

0.1AU) of a MMEN maintains a smooth profile despite a steep decline of planet occurrence rate: a result that favors the truncation of disks by co-rotating magnetospheres with a range of rotation periods, rather than the sublimation of dusts. The Σ of {\it Kepler} multi-transiting systems shows a much stronger correlation with M⋆ and [Fe/H] than singles. This suggests that the dynamically hot evolution that produced single systems also partially removed the memory of formation in disks. Radial-velocity planets yielded a MMEN very similar to CKS planets; transit-timing-variation planets' postulated convergent migration history is supported by their poorly constrained MMEN. We found that lower-mass stars have a higher efficiency of forming/retaining planets: for sun-like stars about 20\% of the solid mass within ∼1AU are converted/preserved as sub-Neptunes, compared to 70\% for late-K-early-M stars. This may be due to the lower binary fraction, lower giant-planet occurrence or the longer disk lifetime of lower-mass stars.

Planetary and Brown Dwarf Companion Mass Ratio Distribution versus Stellar Mass and Orbital Separation - Michael Meyer (Univ. of Michigan)

Understanding the demographic properties of multiple stars as well as planet populations can provide profound constraints on theories of star and planet formation. Surveys for very low mass companions to stars from M to A types as a function of orbital separation naturally detect very low mass brown dwarfs which are a logical extension of binary star formation as well as exoplanets formed through diverse processes in circumstellar disks in Keplerian rotation. We fit the orbital distribution of planetary mass companions around M, FGK, and A stars with a log-normal distribution that peaks between 3-6 AU (Meyer et al. 2018; Meyer et al. to be submitted). Combining these new results with extrapolations of binary star data, we propose a new parametric model for the companion mass ratio distribution (CMRD) as a function of central host star mass from 0.3-3 MSUN sun that includes very low mass brown dwarf companions formed through "binary-like processes" as well as a "planet-like" mass function. The model predicts binary companions well into the brown dwarf regime as well as exoplanet populations as a function of planet mass and orbital radius. These predictions are found to be consistent with many point estimates of companion fraction as a function of mass ratio and orbital separation ranges for diverse host star samples. We find: a) the brown dwarf "desert" is expected as the natural extension of binary and gas giant planet properties; b) local minima in the CMRD occur between 10-40 Jupiter masses depending on host star mass and orbital separation; and c) in binary companions as well as gas giant planet formation, a key parameter is the ratio of the companion to the host star mass from M to A stellar types.

Spitzer Microlens Parallaxes: Connecting Microlensing Planets to the Broader Planet Distribution - Jennifer Yee (CfA)

It is difficult to incorporate microlensing planets into the broader planet population because of the uncertainties in the physical parameters of microlensing planets (e.g. host mass, planet mass, semi-major axis). However, simultaneous observations from Spitzer and Earth can resolve these uncertainties by measuring the parallax effect. This effect combined with the finite source effect allows measurements of not only the masses of the planets and their stars, but also the distances to the planetary systems. Thus, the Spitzer microlensing planet sample is the best-characterized, statistical sample of microlensing planets. It will provide insight into the broader properties of microlensing planets (e.g., Are the hosts really M dwarfs?) and how to integrate them with results from other techniques, and it will demonstrate the pathway to measuring the distribution of planets as a function of Galactic environment.

A Universal Break in the Planet-to-star Mass Ratio: Implications for Planets around Brown Dwarfs - llaria Pascucci (LPL, U of A)

Following the microlensing approach, we quantify the occurrence of Kepler exoplanets as a function of planet-to-star mass ratio (q) and find that the occurrence rate versus q can be described by the same broken power law with a break that is independent of host type for hosts below 1 Msun. The break in q for the microlensing planet population, which mostly probes the region outside the snowline, is ~3-10 times higher than that inferred from Kepler. We show that these results are expected in the most recent pebble-driven planet formation scenario and discuss what planets may form around very low-mass stars and brown dwarfs.

Full-lifetime Simulations of Planetary Systems - Dimitri Veras (Univ. of Warwick)

Our understanding of exoplanet demographics is aided by the analysis of planetary systems at all stages of stellar evolution. Here I will summarize a series of our recent publications which link together the evolution of planetary systems throughout the main-sequence, giant branch and white dwarf phases of the host star. We have self-consistently modelled a multi-planet system with an exo-Kuiper belt from its birth within a stellar cluster to its death around a white dwarf, and separately have constrained the often-ignored prospects for planet formation around B-type and O-type stars by analyzing the demographics of metal-polluted white dwarfs. I will also set bounds on the formation and main-sequence evolution of the evaporating or disrupted ice giant planet recently reported to orbit white dwarf WD J0914+1914.

Nature vs. Nurture: A Bayesian Framework for Assessing Apparent Correlations Between Planetary Orbital Properties and Stellar Ages - Emily Safsten (Penn State)

As more data on exoplanets have been collected, some apparent correlations between planetary and stellar properties have started to emerge. However, the true nature of such correlations is often unclear as stellar properties are often interrelated. In particular, it is unresolved whether these correlations are due to the age of the system -- pointing to evolution over time being an important factor -- or other parameters to which the age may be related, such as stellar mass or stellar temperature. The situation is complicated further by the possibilities of selection biases, small number statistics, uncertainties in stellar age, and orbital evolution timescales that are typically much shorter than the range of observed ages. Here we develop a Bayesian statistical framework to assess the robustness of such observed correlations and to determine whether they are indeed due to evolutionary processes, are more likely to reflect different formation scenarios, or are merely coincidental. We apply this framework to the case of 2:1 resonances, where it has been proposed that systems with 2:1 resonances tend to be younger than those without, and find nearly equal support for the hypothesis of a correlation with age as for the hypothesis that the apparent trend is coincidental. We also apply this framework to the question of whether stellar obliquities are more correlated with age, more correlated with temperature, or are not related to system properties. The results very strongly favor a relation with temperature, i.e., hot stars have high obliquities and cool stars are aligned with their planetary orbits, which corroborates prior work. Finally, we examine whether the currently available hot Jupiter data truly display a trend of eccentricity due to age, and indeed find very strong support for the hypothesis that the set of known hot Jupiters shows the circularization of orbital eccentricities over time.

Unearthing the Earths: Using TESS and Kepler to Reveal the Primordial Population of Short-Period Planets - Rachel Fernandes (LPL, Univ. of Arizona)

Over the past decade, the Kepler mission was instrumental in the discovery of thousands of Gyr-old exoplanets. A large number of these are short-period planets, most of whose orbits are closer in to their host star than Mercury is to our Sun, whereas only one Earth-size planet has been found in the habitable zone of a solar analogue. Prominent features in this Gyr-old population of short-period planets suggest that planets have evolved with time and that the population of small (<1.8 Rearth) short-period planets, which is extrapolated to the habitable zone to estimate the frequency of habitable zone Earth-size planets (hereafter EtaEarth), is contaminated by the bare cores of once sub-Neptune planets. This begs the question: What was the primordial population of short-period planets and how did it evolve with time? One way to answer this question and quantify the contamination of once sub-Neptune planets to EtaEarth is by measuring the occurrence of these planets in young clusters (~10-500 Myr), before their envelope is stripped away. We will discuss our ongoing effort to discover primordial sub-Neptunes in young (<500 Myr) clusters using TESS FFIs and preliminary results on an improved EtaEarth. Our investigation will provide unique constraints to planet formation models, clarify how planetary atmospheres and radii evolve with time, and lend a more reliable EtaEarth estimate - a key parameter to evaluate the yield of nearby Earth analogs that can be detected and characterized by future missions.

Planetary Archaeology: Exploring the Planet Population of Evolved Stars with TESS - Samuel Grunblatt (AMNH)

Most planet searches to date have focused largely on solar-like stars. However, with the advent of large all-sky surveys like TESS and Gaia, comprehensive planet searches are extending from the often targeted FGK and M dwarf stars to more extreme stellar hosts, such as red giants. The long, eventful lives of these systems gives us unique insights into the inflation, evolution and longevity of planets, and the intrinsic brightness of giant stars allows us to robustly characterize planet demographics on larger scales within our Galaxy. Previous studies with Kepler and K2 have revealed that these systems do exist, but our knowledge about them has been seriously limited by the paucity of targets. This issue has now been resolved thanks to the abundance of full frame image data from TESS. Here, I will present the newest discoveries of planets and planet candidates orbiting evolved stars with data from TESS and Gaia. Through a combination of ground- and space-based observation, we are using these systems to test theories of planet inflation and engulfment, explore giant planet occurrence as a function of stellar mass, and investigate properties of planet populations on kiloparsec scales for the first time.

Exoplanet Demographics with White Dwarfs

Observations of Post-Main-Sequence Planetary Debris Disks - Erik Dennihy (Gemini Observatory)

Frequently detected across a wide range of stellar classes, debris disks provide more than just a snapshot of the stages of planetary formation. Features such as gaps, rings, and the ongoing evolution that these disks exhibit shine light on complex, hierarchical planetary systems that will someday become difficult to observe once the planetary system is formed. Beyond the main-sequence, a different kind of debris disk around stellar remnants can likewise provide insight into planetary systems that escape direct detection, but in this case through a process of planetary destruction as opposed to planetary formation. In this review talk, I will discuss the state of observations of debris disks around white dwarf stars, remnant of solar-type stars with circumstellar disks populated by the remnants of now unstable planetary systems. This class of debris disks offers an independent view of the frequency of hierarchical planetary formation, and observations of variability on timescales of hours, days, and years inform the same physical process that govern the evolution of their main-sequence counterparts.

Cold Gas Giant Planets Evaporated by Hot White Dwarfs - Matthias Schrieber (Universidad de Valparaiso)

All known exo-planet host stars will eventually evolve into white dwarfs, their burnt-out cores left behind after the end of the fusion of hydrogen and helium. It is observationally well established that many white dwarfs are accreting small planetary bodies, including asteroids and comets. Gravitationally scattering such planetesimals towards the white dwarf requires the presence of more massive bodies, yet no planet has so far been detected at a white dwarf. We have discovered a moderately hot white dwarf that is accreting from a circumstellar gaseous disc composed of hydrogen, oxygen, and sulfur. The composition of the disc is unlike all previously detected gaseous disks around white dwarfs but resembles predictions for deeper atmospheric layers of icy gas giants, with H2O and H2S being major constituents. We therefore suggest that a gas giant orbiting the white dwarf with a semi-major axis of approximately 15 solar radii is evaporated by the strong extreme-ultraviolet irradiation from the white dwarf. This discovery represents the so far clearest evidence for the expected existence of gas giant planets around white dwarfs and was recently published in Nature.

We extend on this result by calculating the orbital separation at which gas giant planets will be evaporated by hot white dwarfs. We find that the hottest white dwarfs (60.000-100.000K) are bright enough at EUV wavelengths to generate hydrodynamic escape in gas giants located at separations up to 100 au. Even somewhat cooler white dwarfs may still evaporate giant planets at separations of 10-30 au. A fraction of the evaporated material will be accreted by the white dwarf and generate detectable absorption features. Hot white dwarfs can therefore be used to constrain the fraction of gas giant planets around white dwarfs and their progenitor stars. We find that the observed volatile accretion onto hot white dwarfs can be fully explained if at least 50 per cent of hot white dwarfs (and therefore also their main sequence progenitor stars) host gas giant planets beyond a few au.

Doppler Imaging of a Second Planetary Debris Discs Around a White Dwarf - Christopher Manser (Imperial College London)

There is considerable evidence of the survival of planetary material around white dwarfs, the remnant stellar end-points for the majority of planet-hosting stars. One such piece of evidence is the debris discs that orbit within ~1 solar radius of the white dwarf produced by the tidal disruption of a planetesimal. A rare subset of these discs reveal emission from a gaseous component, which can be used to study the dynamical and physical properties of these discs.

In this talk I will present the second image of a gaseous debris disc around a white dwarf produced using Doppler tomography - a technique analogous to CT scanning in hospitals. I will discuss the importance of these images in enhancing our understanding of both the physics of planetary accretion discs as well as the process of the tidal disruption of planetary bodies around white dwarfs. I will conclude with the open questions surrounding debris discs around white dwarfs, and the future prospects for these exciting systems.

Exoplanet Demographics with Stellar Environment

The Impact of Binary Stars on Exoplanet Demographics and Survey Statistics - Maxwell Moe (University of Arizona)

The majority of solar-type stars are born in binaries. Close binaries (a < 50 AU) in particular truncate the mass and longevity of protostellar disks and therefore significantly sculpt planet formation. Indeed, multiple surveys of various types of planet hosts all demonstrate that close binaries suppress planet formation. In this review, I will discuss these surveys and highlight how binary stars affect the observed exoplanet demographics. For example, ~40% of solar-type stars do not host close planets due to suppression by close binaries. The close binary fraction increases with stellar mass and decreases with metallicity, which significantly biases the inferred exoplanet trends with host star parameters. I will also demonstrate how selection effects due to close binaries account for previously unexplained exoplanet anomalies, such as the discrepancy in hot Jupiter occurrence rates measured from radial velocity versus transit techniques and the apparent enhancement of wide stellar companions to hot Jupiter hosts. In the end, I will show how a vetted planet population from the all sky view of TESS can further leverage the true planet occurrence rates with respect to stellar mass and metallicity. I will also emphasize eta_Earth within the context of binary stars and suggest strategies for finding the nearest Earth analogs.

The Demographics of Circumbinary Planets to Help Understand Planet Formation and Migratory Processes - Amaury Triaud (University of Birmingham)

Circumbinary planets orbit around both stars of a binary system. The presence of a binary is thought to affect the accumulation of dust and planetesimals into planets close to the binary. Yet most planets detected thus far are close to their binary. As such the existence of circumbinary planets demonstrates that disc-migration is an effective form of transport within a disc, for super-Earths and for gas-giants.
I will report on preliminary results of the only radial velocity survey dedicated to circumbinary planets currently in operation. We are monitoring 100 single-line eclipsing binaries, north and south seeking planetary candidates. The first stage of our southern survey ended recently, with the identification of 15 candidate signals. One of our systems was also found to host a transiting planet by the TESS mission. Our goal is to compare one to one, the population properties of planets orbiting single stars, to planets orbiting binaries. Our early results confirm that circumbinary planets are quite frequent, as well as confirm a suspicion that circumbinary planets with masses in excess of 1 Mjup are rare. Combining our results to Kepler detections of circumbinary planets, we can draw conclusions on the mutual inclination distribution between planetary and binary orbital planes.

Highly Inclined Planets Around Eccentric Orbit Binaries - Steve Lubow (STScI)

One of the key discoveries of the Kepler mission was the detection of transiting circumbinary planets. By the nature of the detection technique, these planets are preferentially found on nearly coplanar orbits with the binary. We (Martin and Lubow 2017; Lubow and Martin 2018) have shown through analytic modeling and hydrodynamical simulations that a mildly inclined gaseous circumbinary protoplanetary disk around an eccentric orbit binary can naturally evolve to a highly inclined polar orbit that is perpendicular to the binary orbital plane. Planets formed in such a disk would orbit around the semimajor axis of the binary, instead of the binary angular momentum vector. Such a disk was recently discovered in HD98800 by Kennedy et al. (2019) using ALMA. In our model, the coplanarity of the Kepler detected planets is a natural outcome of the generally low eccentricities of the central binaries. The low eccentricities are in turn a consequence of the fairly short binary orbital periods in these systems. We predict that there should exist a significant population of highly inclined planets around eccentric orbit binaries at longer orbital periods than studied by Kepler. New missions such as TESS are in a good position to search for such planets using eclipse timing variations of the binary.

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Exoplanet Atmosphere Demographics

A Review of the Exoplanet Atmosphere Demographics - Johanna Barstow (UCL)

On the Taxonomy of Exoplanets Using Transmission Color Analysis - Kristin Sotzen (JHU)

The majority of exoplanets found to date have been discovered via the transit method, and transmission and emission spectra represent the primary method of studying these distant worlds. Current methods of characterizing transiting exoplanets entail the use of spectrographs on large telescopes, requiring significant observation time to study each planet. However, Crow et al (2011) showed that color-color reflectance ratios can be used to broadly categorize solar system bodies, and Sing et al (2016) and Stevenson (2016) showed trends in hot Jupiter water abundances as a function of blue-optical vs NIR/MIR altitude differences and temperature/gravity respectively. Batalha et al (2018) also showed that it is possible to classify giant planets in color-color space using WFIRST-like filters for planets that do not have significant cloud coverage. Grenfell et al (2020) went on to show the utility of transmission depth differences for the filters of the PLAnetary Transits and Oscilllations of stars (PLATO) mission, showing that basic atmospheric types (primary and water-dominated) and the presence of sub-micron hazes could be distinguished for some planets.

Building on these concepts, we are investigating the use of transmission color-color analysis for coarse categorization of exoplanets as well as assessing the nature and habitability of these worlds, with a focus on resolving the mass/radius degeneracy to aid in discriminating super-Earths and sub-Neptunes. We will present our results, including spectrum models, model comparison frameworks, and waveband selection criteria.

This method could allow for broad characterization of a large number of planets much more efficiently than current methods permit. For example, a TESS follow-on mission could observe multiple band transits to identify exoplanets by category and to break degeneracies between planet size and density (e.g., rocky vs icy). Additionally, data collected via this method could inform follow-up observing time of large telescopes for more detailed study of worlds of interest.

Finally, these data could be used to study planetary system structure for different types and ages of stars, with potentially significant impact to our understanding of planetary system formation and evolution.

Understanding the Radius Valley as a by-product of Planet Formation: Observational Signatures of the Core-Powered Mass-Loss Mechanism - Akash Gupta (UCLA)

Observations have revealed a lack of planets of sizes ~1.5-2.0 Earth radii, i.e. a radius 'valley' in the size distribution of small, short-period exoplanets. This observation has been typically attributed to atmospheric mass-loss due to photoevaporation. However, in recent work, Ginzburg et al. (2018) and Gupta and Schlichting (2019, 2020) have demonstrated that atmospheric mass-loss, powered by the cooling luminosity of the planetary core, yields a valley in the exoplanet size distribution, even in the absence of any photoevaporation or any other process. In my talk, I will describe the key physical processes that drive this core-powered mass-loss mechanism, present detailed comparisons with observations and discuss our recent results that make testable predictions for the core-powered mass-loss mechanism as a function of stellar mass, metallicity and age. I will show that, consistent with observations, the core-powered mass-loss mechanism produces a radius valley that moves to larger planet radii as a function of stellar mass. We thus find no evidence for a linear correlation between the planet and stellar mass, however, we can't rule it out either. Furthermore, under core-powered mass-loss, we find that planets typically lose the bulk of their atmospheres on ~ Gyr timescales to become super-Earths whereas under photoevaporation, this happens in the first ~ 100 Myr. We thus expect even ~ Gyr old planets to be undergoing atmospheric mass-loss. I will conclude with presenting expected atmospheric mass-loss rates among other observational tests to assess the importance of the core-powered mass-loss mechanism.

Unveiling the Planet Population at Birth - James Rogers (Imperial College London)

Recent Kepler data has shown that the radius distribution of small, close-in exoplanets is bimodal. Such bimodality was expected from photoevaporation models of close-in super-Earths, where some planets are stripped of their primordial H/He atmospheres, whilst others retain them. We present a hierarchical inference model on the distribution of Kepler planets using the photoevaporation evolution model. This approach is used to place key constraints on the planetary distributions for core composition, core mass and initial envelope mass-fraction, as well as test other models of planet evolution such as core-powered mass-loss. This new information has interesting implications on planet formation models and also hints at additional atmospheric mass-loss mechanisms.

To Cool is to Keep: Residual H/He Atmospheres of Super-Earths and sub-Neptunes - William Misener (UCLA)

Current theory predicts that observed rocky super-Earths accreted large nebular hydrogen/helium envelopes before disk dispersal. These atmospheres have since been mostly lost through hydrodynamic outflows. Such super-Earth atmospheres may soon be observable, but their mass, composition, and redox state resulting from their evolution are largely unexplored, despite these processes' potential impact on habitability. I will present the observable outcomes of the evolution of super-Earths from their initial states since disk dispersal. Using theoretical models, I will demonstrate that loss of the primordial atmosphere can be incomplete, leading to a thin residual H/He envelope. The masses of these remnant atmospheres vary by orders of magnitude depending on the planet's mass and the flux it receives from its host star. Super-Earths finish mass loss with atmospheric masses ranging from 10^-9 to 10^-2 planet masses for typical parameters. I will discuss the implications of this residual hydrogen for subsequent secondary atmospheres, including their masses, composition, and observational signatures.

Future Exoplanet Demographics Missions

Introduction to the Capabillities of Future Missions: Webb, Roman, Rubin, Euclid, ARIEL, PLATO - various speakers

Roman: Direct-imaging in Reflected Starlight with NGRST: Detectability of Confirmed Exoplanets and Population Analysis - Óscar Carrión-González (Technische Universität Berlin)

The Nancy Grace Roman Space Telescope (NGRST, formerly named WFIRST) will be the first mission to directly image exoplanets in reflected starlight. This will allow us to analyse cold and temperate exoplanets, which cannot be accessed by current facilities. So far, atmospheric characterization is achieved mainly through transit and occultation measurements, which biases these studies towards hot planets in close-in orbits. Direct-imaging observations of long-period planets in reflected starlight will increase our knowledge on the diversity of exoplanets and their atmospheres. This will also affect the theories explaining the formation and evolution of such planetary systems and their architectures. In this work, we studied the exoplanet detection yield of NGRST and future concepts such as LUVOIR or HabEx. For that, we explored the NASA Exoplanet Archive and computed, for all confirmed exoplanets, a range of possible orbital solutions based on their Keplerian parameters and corresponding uncertainties. From that, we obtained the probability of detection and the observational configurations in each case. We analysed the particularities of this subset of detectable exoplanets in comparison with other populations such as the transiting planets. In addition, we discussed the possibilities of retrieving atmospheric properties from direct-imaging measurements of these exoplanets and identified the most favourable targets for such studies.

Direct-imaging observations in reflected starlight are expected to be available in this decade. Here we conclude that NGRST will be able to detect a set of long-period exoplanets which is large enough to begin statistical studies of this population. This will help complete the big picture of exoplanet diversity. The coming years until this mission is launched should allow the community to define the most interesting targets to be observed and improve their orbital solutions.

Roman & Rubin: The Potential of Complementary Survey Strategies - Rachel Street (LCO)

The Nancy Grace Roman Space Telescope (NGRST) is scheduled to begin a survey of the Galactic Bulge mid-way through the all-southern-sky Legacy Survey of Space and Time (LSST) on the Rubin Observatory. The Rubin Observatory are now investigating a range of alternative survey strategies aimed at maximizing the overall science return, so it is timely to explore how the data from these two great observatories may be combined.

The goal of the NGRST Bulge survey is to conduct a census of the exoplanet population at separations from their host stars of ~1-10AU, and of free-floating planets, but constraints on its scheduling will lead to unavoidable gaps in the data timeseries of several months at least. I will discuss how LSST can complement this survey strategy to increase the fraction of planets discovered and fully characterized.

The Rubin Observatory will also detect microlensing events outside the Bulge in substantial numbers, allowing us to explore otherwise hidden populations in different Galactic environments and the Magellenic Clouds. I will discuss preparations to detect and characterize these events.

The Roman Galactic Exoplanet Survey: Predictions for the Free-Floating Planet Detection Rate - Samson Johnson (Ohio State Univ.)

The Nancy Grace Roman Space Telescope (Roman) will perform a Galactic Exoplanet Survey (RGES) to discover bound exoplanets with semi-major axes greater than 1 au using gravitational microlensing. Roman will even be sensitive to planetary mass objects that are not gravitationally bound to any host star. Such free-floating planetary mass objects (FFPs) will be detected as isolated microlensing events with timescales shorter than a few days. A measurement of the abundance and mass function of FFPs is a powerful diagnostic of the formation and evolution of planetary systems, as well as the physics of the formation of isolated objects via direct collapse. Roman will be sensitive to FFP lenses that have masses from that of Mars (0.1 M_Earth) to gas giants (roughly greater than 100 M_Earth) as isolated lensing events with timescales from a few hours to several tens of days, respectively. The number of detections will depend on the abundance of such FFPs as a function of mass, which is at present poorly constrained. Assuming that FFPs follow the fiducial mass function of cold, bound planets adapted from Cassan et al. 2012, we estimate that Roman will detect ~250 FFPs with masses down to that of Mars (including ~60 with masses < 1M_Earth). Roman will improve the upper limits on FFP populations by at least an order of magnitude compared to currently-existing constraints.

Constraining Formation Pathways for Widely-Separated Companions with JWST - Arthur Adams (Univ. of Michigan)

The formation histories of many directly imaged companions are still highly uncertain. Of specific interest are objects within a range of masses, relative to their primaries, which separates those that likely form via planetary pathways, and those which likely form via stellar pathways. Accurate constraints on the compositions of objects with these intermediate mass ratios, specifically their bulk C/O ratios, will help distinguish their formation histories. We present ongoing work to develop accurate retrieval tools for directly imaged sub-stellar companions. Our particular focus is on young imaged L-type companions, whose accurate atmospheric retrieval presents a greater challenge than their cooler T-type counterparts. Nevertheless, with appropriate tools such objects will be characterizable with JWST, whose capabilities complement ongoing ground-based observations.

Atmospheric Characterization of Exoplanet Populations with the James Webb Space Telescope - Knicole Colon (NASA GSFC)

The number of known exoplanets has skyrocketed over the past decade, thanks in large part to the Kepler and K2 missions and the Transiting Exoplanet Survey Satellite (TESS). From these missions, thousands of exoplanets and candidates have been discovered and distinct populations of exoplanets have emerged. One key way to understand different populations of exoplanets is to investigate the atmospheric properties of exoplanets, since the atmospheric composition of an exoplanet provides insight into its formation pathway. The James Webb Space Telescope (JWST), which is slated to launch in 2021, will offer unprecedented sensitivity enabling detailed studies of the atmospheres of transiting exoplanets in particular. In this presentation, I will provide an overview of JWST, including its current status, its capabilities for transiting exoplanet observations, and details about the goals, targets, and timelines of the Early Release Science (ERS) and Guaranteed Time Observations (GTO) transiting exoplanet programs. The ERS and GTO targets notably span a wide range of planet masses and temperatures, allowing us to explore a large parameter space and investigate how atmospheric properties correlate with other planet or stellar properties. Additional General Observer (GO) targets from the community will augment the ERS and GTO programs to provide an even more diverse population of exoplanets to study as well as additional opportunities for comparative exoplanetology. All together, we can expect to make significant progress in our understanding of the atmospheres of exoplanets and the formation pathways of different populations of exoplanets in the era of JWST.

ARIEL: The Pursuit of a Meticulous Chemical Survey of Exoplanet - Billy Edwards (UCL)

Thousands of exoplanets have now been discovered with a huge range of masses, sizes and orbits. However, the essential nature of these planets remains largely mysterious: there is no known, discernible pattern linking the presence, size, or orbital parameters of a planet to the nature of its parent star. We have little idea whether the chemistry of a planet is linked to its formation environment, or whether the type of host star drives the processes controlling the planet's birth and evolution.

Ariel, the ESA M4 mission which will launch in 2028, will characterise the atmospheres of ~1000 exoplanets with instruments providing simultaneous spectral coverage from 0.5-7.8 microns. By studying a large and diverse population of exoplanetary atmospheres, Ariel will offer profound insights into planetary formation and evolution within our galaxy. However, much work still needs to be completed to ensure Ariel is utilised effectively and efficiently. Current facilities and near-future missions such as JWST can help shape our understanding of potential chemical trends and thus improve the observing strategy of Ariel. Developing strategies to exploit the synergies and complementarities between different facilities will be crucial in maximising the scientific yield of these missions.

I will present the latest study of potential targets for Ariel, discuss projects which seek to understand the key capabilities and niches of upcoming space-based observatories, and highlight areas which require additional investigation.

Panel on Synergy of Future Missions - various speakers