Exoplanets and Planet Formation

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Abrupt climate transition of icy worlds from snowball to moist or runaway greenhouse

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Ongoing and future space missions aim to identify potentially habitable planets in our Solar System and beyond. Planetary habitability is determined not only by a planet's current stellar insolation and atmospheric properties, but also by the evolutionary history of its climate. It has been suggested that icy planets and moons become habitable after their initial ice shield melts as their host stars brighten. Here we show from global climate model simulations that a habitable state is not achieved in the climatic evolution of those icy planets and moons that possess an inactive carbonate–silicate cycle and low concentrations of greenhouse gases. Examples for such planetary bodies are the icy moons Europa and Enceladus, and certain icy exoplanets orbiting G and F stars. We find that the stellar fluxes that are required to overcome a planet's initial snowball state are so large that they lead to significant water loss and preclude a habitable planet. Specifically, they exceed the moist greenhouse limit, at which water vapour accumulates at high altitudes where it can readily escape, or the runaway greenhouse limit, at which the strength of the greenhouse increases until the oceans boil away. We suggest that some icy planetary bodies may transition directly to a moist or runaway greenhouse without passing through a habitable Earth-like state.

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Formation of Super-Earths by Tidally-Forced Turbulence

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The Kepler observations indicate that a large fraction of exoplanets are super-Earths, which brings about an intriguing puzzle for the core accretion scenario of planet formation. Since observed super-Earths are in the range of critical mass, they would accrete gas efficiently and grow into gas giants. Theoretically, super-Earths are predicted to be rare in the framework of core accretion. To resolve this contradiction between theory and observation, we propose that the tidally-forced turbulent diffusion may affect the heat transport inside the planet's envelope. Thermal feedback induced by turbulent diffusion is carefully investigated. We find that the tidally-forced turbulent stirring would generate a pseudo-adiabatic region within the radiative zone, which pushes the radiative-convective boundaries (RCBs) inwards. This would decrease the cooling luminosity and enhance the Kelvin-Helmholtz (KH) timescale. For a given lifetime of protoplanetary disks (PPDs), there exists a critical threshold for the tidally-induced turbulent diffusivity, $\nu_{\rm critical}$. If the turbulent diffusivity $\nu_{\rm turb} > \nu_{\rm critical}$, the KH timescale is longer than the disk lifetime. In this case, the planet would become, due to the lack of gas in disks, a super-Earth rather than a gas giant. We find that even a small value of turbulent diffusion has influential effects on the thermal evolution of super-Earths. The value of $\nu_{\rm critical}$ increases with the core mass. We further ascertain that, within the minimum mass extrasolar nebula (MMEN), the critical turbulent diffusivity, $\nu_{\rm critical}$, increases with the semi-major axis. This may explain the observational feature that super-Earths are common in inner PPD regions, while gas giants are common in the outer PPD regions.

3

Clearing Residual Planetesimals By Sweeping Secular Resonances In Transitional Disks: A Lone-Planet Scenario For The Wide Gaps In Debris Disks Around Vega And Fomalhaut

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Extended gaps in the debris disks of both Vega and Fomalhaut have been observed. These structures have been attributed to tidal perturbations by multiple super-Jupiter gas giant planets. Within the current observational limits, however, no such massive planets have been detected. Here we propose a less stringent 'lone-planet' scenario to account for the observed structure with a single eccentric gas giant and suggest that clearing of these wide gaps is induced by its sweeping secular resonance. With a series of numerical simulations, we show that the gravitational potential of the natal disk induces the planet to precess. At the locations where its precession frequency matches the precession frequency the planet imposes on the residual planetesimals, their eccentricity is excited by its resonant perturbation. Due to the hydrodynamic drag by the residual disk gas, the planetesimals undergo orbital decay as their excited eccentricities are effectively damped. During the depletion of the disk gas, the planet's secular resonance propagates inward and clears a wide gap over an extended region of the disk. Although some residual intermediate-size planetesimals may remain in the gap, their surface density is too low to either produce super-Earths or lead to sufficiently frequent disruptive collisions to generate any observable dusty signatures. The main advantage of this lone-planet sweeping-secular-resonance model over the previous multiple gas giant tidal truncation scenario is the relaxed requirement on the number of gas giants. The observationally inferred upper mass limit can also be satisfied provided the hypothetical planet has a significant eccentricity. A significant fraction of solar or more massive stars bear gas giant planets with significant eccentricities. If these planets acquired their present-day kinematic properties prior to the depletion of their natal disks, their sweeping secular resonance would effectively impede the retention of neighboring planets and planetesimals over a wide range of orbital semi-major axes.

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Dust-free modeling of dusty protoplanetary disks

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Understanding the interaction between gas and dust is critical to any planet formation theory. However, modeling dusty gas can be challenging for both analytical and numerical studies, especially for small particles that are strongly but not perfectly coupled to the gas. We present a novel approach to circumvent this difficulty by showing that the equations of dust-gas dynamics can be mapped back to standard hydrodynamics under reasonable assumptions. We can thus model two-phased dusty gas by using single-phase fluid equations. We demonstrate the validity of this approach in both analytical and numerical applications by reproducing well-known results such as dust-trapping at planet gaps, the streaming instability, and dust settling in protoplanetary disks. We also present new results on disk-planet interaction and torques in the limit of high dust-to-gas ratios.

5

Vertical shear instability in dusty protoplanetary disks

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The vertical shear instability (VSI) is a hydrodynamic instability applicable irradiated parts of protoplanetary disks, where the disks's angular velocity varies with height from the mid-plane due to a radial temperature gradient. The VSI taps into this free energy and the result is hydrodynamic turbulence. This is expected to have important effects on the evolution of dust grains in the disk. However, previous analytical studies of the VSI have been restricted to purely gaseous disks. By utilizing a recently-developed framework for studying dusty gas dynamics, we generalize VSI theory to include tightly coupled dust particles. We show that dust-loading generally stabilizes the VSI. Thus VSI activity in a protoplanetary disk directly depends on the vertical dust distribution. Importantly, we show that these results can be understood by drawing on the physical analogy between dust-loading and buoyancy in an adiabatic gas.

6

New Frontier of Exoplanetary Science: High Dispersion Coronagraphy

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Thousands of exoplanets have been discovered, but only a handful of them are amendable for atmospheric spectroscopic study. Spectroscopy leads to understanding of physical and chemical processes taking place in an exoplanet. Spectroscopy of exoplanets can also detect biomarkers in potential habitable planets around other stars. The high dispersion coronagraphy (HDC) provides a pathway to search for biomarkers in planets around M dwarfs with next-generation ground-based extremely large telescopes (ELTs, e.g., TMT and GMT). The HDC combines high resolution spectroscopy (HRS) with a coronagraph operating behind an extreme adaptive optics (AO) system. The coronagraph spatially filters out starlight while the HRS spectrally discriminates starlight from planet light, reaching a starlight suppression level that enables biomarker detection. I will discuss a roadmap to achieve this ambitious goal. The roadmap consists of rigorous science cases at different stages of hardware developments, from existing facilities to future instruments on ELTs, and to future space missions such as HabEx/LUVOIR.

7

Searching for Exoplanet from Dome A Antarctica

Prof. ZHANG, Hui[1]

[1] *Naning University*

While the space based exoplanet survey projects (e.g. Kepler) have achieved great success, there is still valuable exoplanetary science that can be done from the ground. This is especially important at some unique sites. Dome A, the highest point of the Antarctic plateau, is one of these sites. In 2008, China established a scientific site at Dome A. Now, in a significant collaboration with Australian astronomers, a large survey project is ongoing there. This is the Antarctic Survey Telescope (AST3) project, consisting of three 0.5m and one 0.1m binocular telescopes located at Dome A . The exoplanet survey is one of the two major scientific aims of AST3. I will review the past of this project , report the recent results of the exoplanet survey in 2016 and introduce the exoplanetary science in the near future(e.g. the KISS project).

8

Migration of low-mass planets in laminar discs

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Planet migration has become a standard ingredient of planet formation theory. It is well known that low-mass planet migration is far too efficient, taking all planets way too close to their central star. Recent models of protoplanetary discs suggest they may be more laminar than previously thought. Planet migration in laminar, nearly inviscid discs shows a rich variety of outcomes that can save young planets from migrating inward too far.

9

Magnetospheric rebound: a mechanism to re-arrange the orbital configurations of close-in super-Earths during disk dispersal

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Disk migration theory predicts that super-Earth planets would end up at resonance due to their differential migration speed. However, Kepler has found that the period ratios of these planets do not show strong pile-ups near mean motion resonances (MMRs). We propose a new mechanism, magnetospheric rebound that rearranges the orbits of the resonant planets during the disk dispersal phase when the magnetospheric cavity expands outward. An analytical expression of torque near the cavity edge is calculated. We conduct N-body simulations of two-planet systems and investigate under which conditions planets can escape resonances. In addition, we make a statistical comparison between the Kepler observations and the simulations. Simulations are performed based on the migration and the in-situ formation scenarios.

10

Measuring the mass of Proxima Cen from a microlensing event

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Proxima Centauri, our closest neighbour, is a low mass M5 dwarf orbiting in a triple system. The mass of this star has been estimated only with mass-luminosity relations so far, which means that large uncertainties affect our knowledge on the proprieties of Proxima. Very recently an Earth mass planet with 11 days period has been discovered around Proxima Cen. To investigate on the mass of this star, an independent method has been proposed: taking advantage of the close passage of Proxima in front of two background stars, it is possible to parametrise the microlensing effect due to these close encounters and estimate the mass of the lens (Proxima) with high accuracy. The two microlensing events occurred in 2014 and 2016, with impact parameters of 1\farcs6 $\pm$ 0."1 and 0."5 $\pm$ 0."1, respectively. Accurate measurements of the background stars positions during the last two years have been taken with the Hubble Space Telescope, and with SPHERE at the Very Large Telescope from the ground. The SPHERE campaign started on March, 2015, and followed for more than two years, with 9 epochs taken. The parameters of Proxima motion on the sky, and the astrometric calibration of the instrument were readjusted using the background stars visible in the IRDIS field of view in each epoch. Here we present the analysis to measure the dynamical mass of Proxima Cen, and how we obtained sub-mas astrometry precision with SPHERE.

11

Why is there no Hilda planet in our Solar System?

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We try to answer the question whether a Hilda planet could stay in a stable orbit in our Solar System. This fact can be confirmed after the results of long-term integration using all the planets. But we wanted to find out how a possible cloud of planetsimals could form such a planet! Thousands of such bodies - most of them Moon-sized – we integrated in the 3:2 MMR region with Jupiter. We found some bodies up to Mars-sized planets which formed within several millions of years. In addition we checked the possible water content of these bodies which is an interesting point for extrasolar planetary systems like 47 UMa hosting a gas giant just outside the habitable zone. This makes a fictitious Hilda planet in this system a candidate for hosting life but there are also other candidates in the large sample of extrasolar planets (www.exoplanets.eu).

12

What JWST will bring to exoplanet origin and characterization

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The James Webb Space Telescope (JWST) which will be launch soon, in October 2018, exhibits a unique combination of high sensitivity and broad wavelength coverage in the infrared (2-28μm), especially well adapted to exoplanet science. Indeed exoplanets programs will use a substantial fraction of the overall JWST time. JWST will sample the diversity of planets of varying masses, densities, orbital semi-major axes, and eccentricities around a variety of host star temperature, masses and metallicities, a unique sample to constrain exoplanet formation. Among the goals, the study of the atmospheres and of mineral signatures of exoplanets, is a promising one. Spectroscopic capability (MIRI, NIRCam, NIRISS and NIRSpec) will allow investigating planetary atmospheres through atmospheric absorption and thermal emission to determine atomic and molecular compositions, to probe the radial and horizontal structures, and possibly to follow evolution, i.e., exoplanet weather. This will be done through accurate measurement of transits with high signal-to-noise ratio. The other approach is direct imaging, using the two imagers MIRI (5-28 μm) and NIRCAM (2-5 μm) equipped with coronagraphs that will give the capability of imaging young giant-medium planets and make detailed study of circumstellar disks. The NIRISS instrument will even allow detecting the signature of liquid water on rocky planets.

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Formation of massive planetary companions and free-floating Jupiters through circumstellar disk fragmentation

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Most of the Sun's nearest neighbors are M-type stars or brown dwarfs. Constraining the origin of such systems, in particular of those of brown dwarfs hosting a brown dwarf or massive planet as a companion, remains a challenge. Here, we present circumstellar disk fragmentation as a possible mechanism for such systems, based on numerical simulations. Circumstellar disk fragmentation results in the formation of multiple companions of varying mass (from super-Jupiters to low-mass stars) in wide and highly unstable orbits. The decay of these systems results in the ejection of massive planets and brown dwarfs, and in frequent physical collisions. Billions of years after formation, the host stars are often left with none, one, or two companions, with a large variety of configurations, including two types of hierarchical triples with predictable (and measurable) orbital configurations. Despite the unknown frequency of occurrence, circumstellar disk fragmentation is able to predict many of the challenging stellar and substellar systems in the solar neighborhood, and provides predictions for the properties of hierarchical systems containing brown dwarfs and massive planets.

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Exo-Nephology: 3D simulations of cloudy hot-Jupiter atmospheres with the UK Met Office climate model.

LINES, Stefan[1]

[1] *University of Exeter*

Recent HST observations of hot Jupiter atmospheres have revealed a continuum in atmospheric composition from cloudy to clear skies. The presence of clouds is inferred from a grey opacity in the near-IR that mutes key absorption features in the transmission spectra. This observational challenge inhibits the retrieval of key information including the atmospheric chemical composition and thermal structure. Unlike the L-T Brown Dwarf sequence, this transition does not correlate well with equilibrium temperature, suggesting that a cloud formation scheme more comprehensive than homogenous cloud growth at the condensation temperature is required. In our work, we follow and extend the pioneering study of Lee et al., (2016) by performing 3D simulations of cloud nucleation, growth, advection, evaporation

and gravitational settling in the atmospheres of HD209458b and HD189733 using the kinetic and mixed-grain cloud formation code DIHRT, coupled to the Met Office GCM, the 'Unified Model'. We explore cloud composition, vertical structure and particle sizes, as well as highlighting the importance of the strong atmospheric dynamics seen in tidally locked hot- Jupiters on the evolution and distribution of the cloud. The completeness of the radiative transfer (i.e. inclusion of scattering) and the dynamics provided by our new model, will represent the most physically complete theoretical tool for the study of hot-Jupiters.

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Dynamical evolution of inner planet systems with outer giant planet scatterings

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The Kepler mission has detected hundreds of multiple planet systems. These systems are typically observed to be close-in (less than 0.5 AU), and their orbits tend to be tightly packed and feature low eccentricities (˜0.02) and inclinations (˜2 deg). We study the dynamical evolution of such inner systems subject to the gravitational effect of an unstable system of outer (> 1 AU) giant planets, focussing on systems whose end configurations feature only a single remaining outer giant. In contrast to similar previous studies which tend to focus solely on N-body simulations with specific parameters or scenarios, we implement a novel hybrid algorithm which combines N-body simulations with secular dynamics with aims of obtaining analytical understanding. We find that the dynamical evolution of the inner planet system depends crucially on N_{ej}, the number of mutual close encounters between the outer planets prior to eventual ejection/merger. When N_{ej} is small, the eventual evolution of the inner planets can be well described by secular dynamics. For larger values of N_{ej}, the inner planets gain orbital inclination, mutual inclination and eccentricity in a stochastic fashion analogous to Brownian motion. We present scaling laws for the final orbital parameters of the inner system, and discuss the implications of our results for the evolution of Kepler multi-planet systems.

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Multiplanet Systems as Laboratories for Planet Formation

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The universe has provided us with multiplanet systems, laboratories in which we can test the physics of planet formation. I will talk about three ways in which we can use multiplanet systems as laboratories. (1) We can study the orbital dynamics of a single multi-planet system in detail. (2) In each multiplanet system, we can compare a planet to its siblings, developing statistics over many systems. (3) We can compare multiplanet systems to systems with only one known planet. My talk will draw on results from the California Kepler Survey, which provided new stellar and planetary properties for 909 transiting planets in 355 multiplanet systems, as well as recent dynamical work.

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Microphysical Modeling of Convective Dust Clouds in Warm Super-Earths

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Recent observations of the transmission spectra of exoplanetary atmospheres have revealed the ubiquity of high-altitude clouds or haze in super-Earths. Understanding the formation processes of super-Earth's clouds is essential to correctly interpret the observed spectra. In this study, we present a one-dimensional microphysical convective dust cloud model for super-Earths of different atmospheric metallicity. Our model for the first time takes into account the condensation, coalescence, and vertical transport of mineral particles in a self-consistent manner. Our model shows that the cloud-top height increases with increasing metallicity as long as the metallicity is lower than a threshold. For metallicities above the threshold, the cloud-top height no longer increases with metallicity because of particle coalescence, which produces larger particles with higher settling velocities. We apply our convective cloud model to GJ1214 b and GJ436 b, for which the presence of a high-altitude cloud or photochemical haze is suggested from recent transmission observations. For GJ436 b, we find that a high altitude cloud can form if the atmospheric metallicity is 100–1000 times higher than solar as suggested by recent planet formation models. For GJ1214 b, the cloud-top height predicted from our model is too low to be consistent with the observed transmission spectrum even if the atmospheric metallicity is extremely high. This indicates that the presence of photochemical haze is a more natural explanation for the flat transmission spectrum of GJ1214 b.

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Vortex survival in 3D self-gravitating discs

LIN, Min-Kai[1]

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Large-scale vortices in protoplanetary discs can act dust-traps that may account for observations of asymmetric transition discs, and may also be sites of accelerated planetesimal formation. The survival of vortices in accretion discs is thus an important issue to address. An often neglected effect when modeling disc vortices is their self- gravity. In this work, we show that disc self-gravity affects 3D vortex evolution even when the Toomre stability criterion is well-satisfied. We present customized numerical simulations of 3D vortex evolution in the shearing box approximation, including disc self-gravity. As expected from previous studies, an 'elliptic instability' develops and destroys non-self-gravitating 3D vortices. However, we find that including moderate disc self-gravity with a Toomre Q˜8 is sufficient to allow vortex survival against the elliptic instability. We observe self-gravitating 3D vortices undergo secular collapse over a timescale of ˜1000 orbits, during which Reynold stresses increase. We hypothesize a feedback loop between a collapsing vortex with decreasing aspect-ratio, generating hydrodynamic turbulence due to elliptic instability, which enables further collapse due to secular gravitational instabilities. Our simulations suggest that large-scale vortices may survive more easily, and hence observable, in protoplanetary discs at large radii, where self-gravity becomes important.

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Pebble Accretion in Turbulent Protoplanetary Disks

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[2] *Tsinghua University*

[3] *University of California, Santa Cruz*

It has been realized in recent years that the accretion of pebble-sized dust particles onto planetary cores is an important mode of core growth, which enables the formation of giant planets at large distances and assists planet formation in general. The pebble accretion theory is built upon the orbit theory of dust particles in a laminar protoplanetary disk (PPD). For sufficiently large core mass (in the "Hill regime"), essentially all particles of appropriate sizes entering the Hill sphere can be captured. However, the outer regions of PPDs are expected to be weakly turbulent due to the magnetorotational instability (MRI), where turbulent stirring of particle orbits may affect the efficiency of pebble accretion. We conduct shearing-box simulations of pebble accretion with different levels of MRI turbulence (strongly turbulent assuming ideal magnetohydrodynamics, weakly turbulent in the presence of ambipolar diffusion, and laminar) and different core masses to test the efficiency of pebble accretion at a microphysical level. We find that accretion remains efficient for marginally coupled particles (dimensionless stopping time $\tau_s \sim 0.1 - 1$) even in the presence of strong MRI turbulence. Though more dust particles are brought

toward the core by the turbulence, this effect is largely canceled by a reduction in accretion probability. As a result, the overall effect of turbulence on the accretion rate is mainly reflected in the changes in the thickness of the dust layer. On the other hand, we find that the efficiency of pebble accretion for strongly coupled particles (down to $\tau_s \sim 0.01$) can be modestly reduced by strong turbulence for low-mass cores.

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Discovering the Interior of Jupiter with Juno

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The key to understand our origins is in the interiors and atmospheres of the giant planets. Jupiter is the biggest planet in our system and the most influential one: its large mass shaped the architecture of the solar system and due to its fast formation it contains valuable information of the solar system formation history. In orbit since July 2016, the first orbits of Juno mission had led to a remarkable improving of the planet gravity data, changing our knowledge of the planetary interior and leading to a much better comprehension of the giant planet and its role in the solar system. In this seminar, I will present the new Juno results, the models we use to understand Jupiter interior and its differential rotation and the main challenges and questions that remained to be solved.

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Mutual Inclinations of Circumbinary Protoplanetary Disks

CZEKALA, Ian[1]

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Measuring the relative inclinations between binary stars and their circumbinary disks is vital for interpreting the census of known *Kepler* circumbinary planets and understanding their formation environment. Through a series of ALMA programs, we have targeted protoplanetary disks around spectroscopic binaries to infer the disk structure, dynamically measure the total stellar mass, and determine the mutual inclinations between the stellar orbits and the circumbinary disk. Thus far, we know of 4 systems with 10-20 day orbital periods that all show alignment to within 3 degrees, which is in remarkable agreement with the mutual inclinations of the *Kepler* circumbinary planets and would seem to suggest that coplanarity is a feature of the short-period binary star and planet formation process. However, we caution that selection effects which make aligned systems easier to detect are potentially at work in both the disk and planet samples. In fact, our ALMA and RV program recently revealed a triple system that has its large circumtriple disk misaligned with at least one and possibly both stellar orbits by as much as 45 degrees. Mapping out and understanding the distribution of mutual inclinations has ramifications for the circumbinary planet occurrence rate—if a significant population of misaligned systems exist, then the circumbinary planets might form even more frequently than their single star counterparts.

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ALMA resolves CI emission from the β Pictoris debris disk

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Dusty debris disks are the product of the continuous collisional destruction of leftover planetesimals. As an outcome of the planet formation process, debris disks allow us to constrain planet formation theories and characterise the building blocks of planets.

A small fraction of debris disks show a gaseous component in addition to the dust. An example is the archetypal debris disk around the young (∼23 Myr) A-star β Pictoris. Similar to the dust, the gas in this system is of secondary origin rather than leftover from the protoplanetary phase. For example, colliding dust grains or outgassing from cometary bodies can produce gas. Studying the gas therefore allows us to constrain the composition of the parent bodies.
Recent ALMA observations of CO emission from the β Pic disk revealed a clump on the SW side of the disk, corresponding to a site of elevated collision rate and thus gas production. The clump has been interpreted as cometary bodies trapped in a resonance with an outward-migrating giant planet or as the result of a recent giant collision. Photodissociation limits the lifetime of CO to ∼100 yr, producing C and O.
I will present the first resolved observations of CI emission. Our ALMA data show an asymmetry similar to what is seen for CO. However, C is expected to quickly spread in azimuth even if it is primarily produced at the clump. This is thus a surprising result that challenges our understanding of the gas production and evolution in this system. I will discuss the implications of the new data, in particular regarding the origin of the observed clump.

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Connecting simulations of disk-planet interactions with observations of protoplanetary disks

Dr. DONG, Ruobing[1]

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Because planets form in protoplanetary disks, the most direct and powerful way to learn how they form from observations is to directly watch them forming in disks. Thanks to a fleet of new instruments with unprecedented resolving power that have come online recently, we have just started to unveil structures in resolve images of protoplanetary disks, such as gaps, spiral arms, and azimuthal asymmetries, that are most likely associated with planets forming in disks. By comparing observations with theoretical models of planet-disk interactions, the masses and orbits of (unseen) planets may be constrained. Such planets can help us directly test various planet formation models. I will review (1) what are the state of the art disk observations that are providing the clearest signposts of planet formation in disks, (2) what kind of comparisons between observations and theoretical models are being done today, and (3) what have we learned so far about planet formation from these observations.

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On the Spin-axis Dynamics of Planets

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The variation of a planet's obliquity plays an important role in determining its climate, and the existence of massive satellites can influence such variations. For instance, the Earth's obliquity is stabilized by the Moon, and would undergo chaotic variations without the Moon. To quantify this, I will present a simplified perturbative approach, and demonstrate that without the Moon, the stochastic change in the Earth's obliquity is sufficiently slow to not reach high values (>40 degrees) in billion-year timescales. In addition, I will apply this analytical approach and show that Earth obtained its current obliquity during the formation of the Moon, when the Solar System was more compact according to the Nice Model. In the end, applying similar techniques to exoplanetary systems, I will illustrate that compact planetary systems generally do not lead to larger obliquity variations, and Kepler-186f, a habitable zone planet, allows little obliquity variations assuming it is an Earth analogue.

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Migration of low mass planets in laminar, magnetically torqued protoplanetary discs

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The theory of low mass planet migration has been developed largely in the context of viscous protoplanetary disc models. Recent simulations of magnetised protoplanetary discs indicate that non-ideal MHD processes lead to the discs being laminar, with angular momentum transport occurring because of torques that are provided by large scale magnetic fields. In this talk I will present the results from a recent study of low mass planet migration in laminar, magnetically torqued discs. This study has shown that the speed and direction of migration depends on the history of both the planet's motion through the disc *and* the magnetic torquing experienced by the disc. The implications of this new picture of planet migration for the formation of planetary systems will be discussed.

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A Panchromatic Comparative View of Exoplanet Atmospheres

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Hubble has played the definitive role in the characterisation of exoplanets and from the first planets available, we have learned that their atmospheres are incredibly diverse. With HST and JWST, a new era of atmospheric studies is opening up, where wide scale comparative planetology and precision abundance measurements will be possible. Hubble's full spectroscopic capabilities are now being used to produce the first large-scale, simultaneous UVOIR comparative study of exoplanets with 20 planets ranging from super-Earth to Neptune and Jupiter sized planets. The panchromatic treasury program aims at build a lasting HST legacy, providing the UV and blue-optical exoplanet spectra which will be unavailable to JWST and give key insights into clouds. The short-wavelength scattering properties are important to constrain in order to break degeneracies and measure precise metallicities. I will present the latest findings from the ongoing Hubble Treasury program, and discuss how JWST will transform the field of exoplanet characterisation.

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Rings, gaps and cavities in protoplanetary disks: How to distinguish between different potential origins?

PINILLA, Paola[1]

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Recent multi-wavelength observations of protoplanetary disks have revealed fascinating structures, such as: multiple rings/gaps, asymmetries, and spiral arms. The most common explanation to understand the origin of these structures is embedded planets. However, alternative models can create similar structures in the gas and dust density distribution of protoplanetary disks. In this talk I will present recent theoretical predictions of models that include a dead zone and/or MHD winds in the context of transition disks. In addition, I will present the effect that several snow lines can have on the dust evolution, following the growth, fragmentation and dynamics of multiple dust size particles. Finally, I'll introduce some observational perspectives to distinguish between different possibilities for the origin of rings, gaps and cavities in protoplanetary disks.

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Back to hot jupiters

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There are 3 scenario to explain hot Jupiters' presence: in-situ growth; smooth migration by a disk; high-eccentricity migration by companions. The last scenario is the best studied but it requires the help of tidal dissipation which is poorly understood. Here, I present some new theoretical results to elucidate how tidal dissipation works in these bodies. There are a number of observational implications, including the locations of hot Jupiters, their eccentricity distributions, their inflated sizes, relationship to warm jupiters, etc.

30

A new distant, eccentric Jovian around HAT-P-11

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We report a new distant, eccentric giant planet around the mid-K dwarf HAT-P-11, based on a decade of precision Radial Velocity (RV) measurements from Keck/HIRES. Previously, this star was known to host a close-in ($P = 4.88$ days), moderately eccentric Neptune-size planet with a nearly polar orbit. The new planet, HAT-P-11c, has $M_p \sin i = 477^{+38}_{-31}\, M_{\oplus}$, $e = 0.601 \pm 0.030$, and an orbital period of nine years. Because HAT-P-11 is a chromospherically active star, we investigate the S_{HK} and H-alpha indices as possible tracers of stellar activity. We perform a joint RV-activity analysis to simultaneously fit for the effects of planets and stellar activity, finding an activity-induced RV signal of around 15 m/s while validating the two-planet RV model. We also investigate the dynamical interactions between the two planets and find that secular perturbations from HAT-P-11c can account for the unusual high obliquity of the inner planet. Furthermore, given its wide orbit ($4.11^{+0.25}_{-0.16}$ AU) and close proximity to earth (26.39 ± 0.23 pc), HAT-P-11c has one of the largest angular separations of any RV-detected planet ($\sim$ 240 mas), presenting good prospects for future direct-imaging and astrometric measurements of the planet.

31

Self-induced dust traps: overcoming planet formation barriers

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Planet formation is thought to occur in discs around young stars by the aggregation of small dust grains into much larger objects. The growth from grains to pebbles and from planetesimals to planets is now fairly well understood. The intermediate stage has however been found to be hindered by the radial-drift and fragmentation barriers.
We identify a powerful mechanism in which dust overcomes both barriers. Its key ingredients are (i) backreaction from the dust on to the gas, (ii) grain growth and fragmentation and (iii) large-scale gradients. The pile-up of growing and fragmenting grains modifies the gas structure on large scales and triggers the formation of pressure maxima, in which particles are trapped.
We show that these self-induced dust traps are robust: they develop for a wide range of disc structures, fragmentation thresholds and initial dust-to-gas ratios. They are favored locations for the formation of pebble-sized solids and their subsequent growth into planetesimals, thus opening new paths towards the formation of planets.

32

Searching for Exoplanetary Rings via Transit Photometry

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The detection of a planetary ring of exoplanets remains one of the most attractive, but challenging, goals in the field of exoplanetary science. We present our ongoing attempt to search for for exoplanetary rings via transit photometry of the Kepler data, and show tentative candidates and resulting constraints on the exoplanetary rings.

33

Towards Realistic Understandings of Gas Dynamics in Protoplanetary Disks

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The gas dynamics and long-term evolution of protoplanetary disks (PPDs) play a crucial role in almost all stages of planet formation, yet they are far from being well understood largely due to the complex interplay among various microphysical processes. Primarily, PPD gas dynamics is likely governed by magnetic field, and its coupling with the weakly ionized gas is described by non-ideal magnetohydrodynamic (MHD) effects. Incorporating these effects, I will present the first fully global simulations of PPDs aiming to incorporate most realistic disk microphysics. Accretion and disk evolution is primarily driven by magnetized disk winds with significant mass loss comparable to accretion rate. The overall disk gas dynamics strongly depends on the polarity of large-scale poloidal magnetic field threading the disk owing to the Hall effect. The flow structure in the disk is highly unconventional with major implications on planet formation.

34

Forming planets and their circumplanetary disks

SZULAGYI, Judit[1]

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With a few ambiguous detections of forming planets today, we still need to understand how young planets and their circumplanetary disk look like on observations and what are the characteristics that can be derived from either the data or from numerical simulations. This is key to understand satellite formation and the late giant planet formation as well. In my talk I will summarize what we know about the circumplanetary disk today, how we can observe them e.g. with ALMA, and what they infer on planet- and satellite formation.

36

The Dharma Planet Survey of Low-mass and Habitable Rocky Planets around Nearby Solar-type Stars

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The Dharma Planet Survey (DPS) aims to monitor ˜150 nearby very bright FGK dwarfs (most of them brighter than V=7) during 2016-2020 for low-mass planets and conduct high precision radial velocity (RV) followup of about 40 transiting planet candidates around bright FGK dwarfs (V<10) from TESS mission in 2019-2020. The TOU optical very high resolution spectrograph (R˜100,000, 380-900nm) is used for high precision RV measurements at the fully dedicated 50-inch Automatic Dharma Endowment Foundation Telescope (DEFT) on Mt. Lemmon. Operated in high vacuum with precisely controlled temperature, TOU has reached ˜0.8 m/s RV precision for bright survey stars. With very high RV precision and high cadence, a large number of rocky planets, including possible habitable ones, are expected to be detected, and transiting planet mass and density, as well as orbital parameters, will be characterized. Early sciences including discoveries of low-mass planets will be presented.

37

Early evolution of protoplanetary disks: a ring-gap structure formation

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Recent observations with ALMA reveal the detailed structures of the protoplanetary disk at the early evolutionary stage. Sheehan and Eisner 2017 found that the ring-gap structure is formed in the protoplanetary disk around the protostar WL 17. The outer radius of the ring is about 20 au and the inner gap is formed within 10 au. Such a gap structure is thought to be the feature of the transition disks. However, the age of WL 17 is estimated to be a few times 10^5 yr. The mechanisms of the gap formation in such young disks have not been investigated well. The gap structure may be formed by the planet. However, the planets forming the gap have not been observed, and it seems difficult to form the planet in the young protoplanetary disks. Thus, it is important to investigate another mechanism for the gap formation in the young disk. In this work, we investigate the gap formation by the disk wind in the young disks like WL 17 using 1D disk model for the formation and evolution of protoplanetary disks. We discuss the condition of the the efficiency of the turbulent viscosity, the mass loss rate by the disk wind, and the dust radius for the gap-opening in young disks.

38

Constraints on the Obliquities of Kepler Planet-Hosting Stars

WINN, Joshua[1]

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Stars with hot Jupiters are observed to have a wide range of obliquities, for reasons that remain unknown. However, most of our knowledge of obliquities has been limited to stars with close-in giant planets, for practical reasons. Relatively little is known about the obliquities of stars with smaller planets. Using data from the California-Kepler Survey, we have investigated the obliquities of stars with planets spanning a wide range of sizes, most of which are smaller than Neptune. The results of several statistical tests suggest that the Kepler planet-hosting stars generally have low obliquities, with the exception of hot stars with hot Jupiters.

39

Establishing the Architectures of Planetary Systems

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I present a synopsis of several studies into the nature and origin of planetary system architectures. These studies include the analysis of several large suites of dynamical simulations investigating the instability of planetary systems, the population of planets discovered by the Kepler mission, and a large sample of radial velocity data to investigate the nature of planetary systems near the 2:1 mean-motion resonance. Together these studies should give insights into the dynamical processes that shape planetary systems.

40

Chemical network reduction in protoplanetary disks

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Realistic studies of protoplanetary disk (PPD) gas dynamics requires accurate knowledge about disk ionization and thermodynamics, both of which depends on chemistry. However, coupling time-dependent chemistry with gas dynamics is usually prohibitively computationally expensive. In this paper, we aim to alleviate this constraint by reducing the size of chemical networks. We follow the species-based network reduction method and conduct network reduction at both the disk midplane and disk surface regions. We found that around 20 gas phase species are adequate for reproducing the abundances of major species within a couple scale heights about the disk midplane, and around 30 gas phase species are needed in the disk surface above Far-UV (FUV) front. The chemistry in between is the most complex and around 80 species are required. These results will be useful for future hydrodynamic/magnetohydrodynamic (MHD) simulations of PPDs, especially by accurately accounting for thermodynamics in disk winds and the overall non-ideal MHD physics.

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Population-Level Analysis of Hot Jupiter Composition, Structure, and Radius Inflation

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There are now more than 300 transiting gas giant planets with well-determined masses and radii. This is a relatively large number, so the population can be studied with the aid of Bayesian statistics to bring out trends in the sample, which can be used to understand the formation and physics of these planets. I will discuss three new inferences that we have made for this population. First is the mass-metallicity relation for gas giants, which show that planet mass dominates over parent-star metallicity in defining the bulk metal-enrichment of these planets. This is a new window into planet formation and giant planet metal-enrichment. Second is the role of anomalous power in inflating hot Jupiter radii. There is strong evidence that this power, as a fraction of the incident stellar power, peaks at planetary Teff=1500 K, as predicted by Ohmic dissipation. Lastly, there is also compelling evidence that these giant planets inflate in radii as their stars brighten on the main sequence (and off the main sequence), suggesting that the cause of hot Jupiter radius anomalies is not merely a delay in their cooling and contraction, but is a deep-seated energy source, which is compatible with some models of Ohmic dissipation.

42

Subaru/HiCIAO High-contrast Near-infrared Observations towards Protoplanetary Disks in Binary Systems

YANG, Yi[1]

[1] *SOKENDAI (The Graduate University for Advanced Studies)*

Currently about 200 planets have ever been discovered in binary or multiple systems. Undoubtedly, to understand their formation process, not only theoretical work but also direct observations towards the protoplanetary disks in young binary/multiple star systems is quite necessary. By high-contrast polarimetry observation with HiCIAO, a high-contrast observation instrument mounted on the 8.2-m Subaru Telescope in Hawaii, the complicated structures around the young binary GG Tau A and T Tau are successfully resolved. By investigating them, we can understand how the binary system will affect the disk evolution as well as planet formation. It could be quite beneficial for us to improve current theories of planet formation process in binary systems.

43

Winds from T Tauri stars

Dr. FANG, Min[1]

[1] *University of Arizona*

Low-excitation forbidden lines of [O I] and [S II] have been frequently observed from classical T Tauri stars, and are interpreted as arising in winds from these young systems. An investigation of the profiles of the forbidden lines suggests that there are at lease two types of components: the high velocity component (HVC) and the low velocity component (LVC). The HVCs have been unambiguously identified with the jets in some cases. But, the origin of the LVC is still unknown. I will present our recent results on origin and physical characteristics of the HVC and the LVC.

44

Dynamic portrait of the planar 3:1 mean motion resonance

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We present in this report the global structure of the planar 3:1 mean motion resonance between two exoplanets. The dynamics is depicted by a Hamiltonian. Inside the resonance, two integrals, namely the total angular momentum and the spacing parameter, reduce the problem to two degrees of freedom. After such simplification and via semi-analytical method, the topology of the Hamiltonian can be described on different representative planes. Using the spectral analysis technique, we then construct the dynamical maps on the representative planes with various values of the total angular momentum, identifying the regions associated with different patterns of motion. For different energy levels, we present for the first time the Poincare maps on the surface of sections and a clear view of the global dynamical features is obtained. Proper frequencies of motion along the stationary solutions are also provided to illustrate the bifurcation phenomenon in the evolution of solutions. The knowledge of the global structure of this resonance system is the basis for the understanding of the formation and evolution of the planetary configuration inside the 3:1 MMR. Beginning with the study in our report, we are aiming to predict and explain all the possible dynamical behaviors of exoplanets trapped in the 3:1 resonance during the planetary migration.

45

Planets around A-stars as anchors for planet migration

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Very few planets have been confirmed around early type main sequence stars, since these are often too rapidly rotating for precise radial velocities to be obtained. Of the ˜1900 transiting planets known today, only eight have been confirmed to transit stars hotter than T>7000K. However, planets around high mass stars are key pieces of the planet formation puzzle, they are important to understanding giant planet formation and migration. For example, the protoplanetary disk mass around A-type stars should be significantly higher than that around solar-type stars, leading to a higher planet occurrence rate, and dynamically hotter systems. The stellar multiplicity rate is also higher for higher mass stars. Will the dynamically hotter environment around A-type planet-hosting stars result in different hot-Jupiter migrational pathways than around solar-type stars? We are using the Doppler tomography technique to confirm and characterise these planets around A-stars. I will detail our recent discoveries with the K2, KELT, and HAT surveys, and describe the next steps in defining the planet migration pathways that lead to these hot-Jupiters in the context of TESS.

46

Orbital Shape and Spacing of Exoplanets: Observational Patterns

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Orbital shape (parameterized with eccentricity) and orbital spacing (parameterized with orbital period ratio of two adjacent planets P2/P1 or the difference in orbital semimajor axis normalized by their mutual Hill radius (a2-a1)/RH) are two fundamental properties of planetary orbits. Combining the photometric observations from Kepler and the spectroscopic observations from LAMOST, we statistically investigate these planetary orbital properties and their relations to the stellar hosts. We find several significant patterns, which provide clues to unveil the history of (exo)planet formation and evolution.

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X-Ray Photoevaporation and the Final Location of Giant Planets

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The location of giant planets in a planetary system can be of high importance for the potential habitability of a planet. It can affect its dynamical evolution as well as the delivery of volatiles to terrestrial planets. By shielding them from severe impacts by asteroids and comets, giant planets can even protect them from becoming inhabitable. Therefore, understanding the formation and the dynamical evolution of giant planets is of utmost importance for the study of planetary systems and the possible consequences for the emergence of life.
Recent exoplanet surveys have highlighted the existence of a mind-blowing diversity of planetary systems as well as well-defined trends. One of these is the peak in the semi-major axis distribution of giant planets at 1-2 au. It has recently been suggested that this distribution may be established during the time of planetary migration in the protoplanetary disc, which is halted by disc dispersal via X-ray driven photoevaporation. We have searched for signatures of this process in the final semi-major axis distribution of giant planets. For this purpose, a catalog containing the X-ray fluxes of all known giant planet hosting stars, which have been observed by *Chandra*, *XMM-Newton* or ROSAT has been produced. We find prominent features in the X-ray luminosity versus semi-major axis plane, which are found to match the results of preliminary numerical simulations. This suggests that X-ray driven photoevaporation may indeed shape the final distribution of giant planets.

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Probing unexplored exoplanet demographics with new microlensing campaigns

SHVARTZVALD, Yossi[1]

[1] *JPL*

Gravitational microlensing is unique in its ability to probe several relatively untapped reservoirs of exoplanet demographics, including planets near the "snowline," the Galactic distribution of exoplanets, and the population of free-floating planets. However, converting from the standard microlensing observables to the fundamental physical properties of the lensing system requires additional information beyond the basic microlensing light curve. In the past few years we have achieved significant advances in developing the two main techniques to derive the planet properties, through measurements of the satellite parallax effect and also the flux of the lensing system. In this talk I will discuss these new efforts and present our key results. Specifically, Spitzer microlensing campaigns from 2014-2017 have measured satellite parallaxes for over 400 events, facilitating mass and distance measurements for the lenses, including several planetary in nature. K2's Campaign 9 built off of this and conducted the first automated microlensing survey from space, providing the first opportunity to measure the masses of free-floating planets, which are identified by their short timescales and are inaccessible to Spitzer given its several-day lag between target selection and observation. Finally, high-resolution observations with Keck allowed us to isolate the microlensing targets and characterize planetary events. These efforts set the stage for the space-based microlensing survey of the WFIRST flagship mission, which was recently approved for Phase A and will extend the exoplanet census begun by Kepler to the outer reaches of planetary systems throughout the Milky Way.

49

Understanding planet formation by understanding atmospheric escape

OWEN, James[1]

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I will discuss the recently discovered gap (Fulton et al. 2017) in the radius distribution of close-in, small exoplanets in the context of atmospheric escape. I will show how such a gap naturally arises from a population of close-in planets when they are composed of a solid core surrounded by a H/He envelope. The properties of the location of the gap are extremely sensitive to the properties of the solid core and can thus be used as a probe of their composition. Using this information I will provide insights as to how the "Kepler" planets formed.

50

Fragmentation of early massive circumstellar disk, with and without MRI turbulence

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We carry out simulations of gravitationally unstable disks using smoothed particle hydrodynamics (SPH) and the novel Lagrangian meshless finite mass (MFM) scheme in the GIZMO code to study the non-convergence of the critical cooling rate for fragmentation reported in the literature. With MFM we demonstrate convergence of the critical cooling timescale for fragmentation at $\beta_{crit} \approx 3$. Non-convergence persists in SPH codes. We show how the non-convergence problem is caused by artificial fragmentation triggered by excessive dissipation of angular momentum in domains with large velocity derivatives.
To find out if physical dissipation of angular momentum by MRI turbulence can lead to fragmentation, we run local shearing box simulations to compare with previous grid code results. The MFM method can correctly evolve MRI turbulence while MRI turbulence in SPH simulations decays due to kernel noise and high divergence of magnetic fields. SPH MRI shearing box simulations leave strong toroidal fields

which are at equipartition with the gas pressure and this problem may have plagued many previous studies.
Preliminary global 3D MRI simulation in a gravitationally unstable disk will be presented.

51

Protostellar disc fragments in SPH simulations

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Using smoothed particle hydrodynamics, we carry out 9 simulations of a 0.25 M$\odot$ protoplanetary discaround a 1 M$\odot$ star, all of which fragment through gravitational instability to form at least 2 boundobjects. We compare these simulations to state-of-the-art population synthesis models, and find thatparameterised models reasonably capture the mass distribution displayed in global simulations. How-ever, fragment-fragment interactions play an important role in the evolution of the system, even whenthe disc is present. We therefore recommend that future population synthesis models include the effectsof fragment-fragment interactions.

52

The role of collisions in water transport and water loss during planet formation

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planet formation and water loss

53

AMD-stability and the classification of planetary systems

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In a planetary system, the AMD (Angular Momentum Deficit) is the difference between the planar circular angular momentum and the total angular momentum. This quantity is conserved between collisions in the average system, and decreases during collisions.
This leads to the concept of AMD-stability. A planetary system is AMD-stable if the AMD of the system is not sufficient to allow collisions. The advantage of this notion is that it becomes possible to verify very quickly whether a newly discovered planetary system is stable or potentially unstable, without any numerical integration of the equations of motion. These principles have been applied to the 131 multiple planetary systems of the exoplanet.eu database whose orbital elements are sufficiently well determined (Laskar and Petit, 2017a).
AMD-stability, based on the secular evolution, addresses to long time stability, in absence of mean motion resonances. On the other hand, criterions for short term stability have been established on the basis of Hill radius (Marchal & Bozis 1982; Gladman 1993; Chambers et al. 1996; Smith & Lissauer 2009; Pu & Wu 2015) or on the overlap of mean motion resonances (Wisdom 1980; Duncan et al. 1989; Mustill & Wyatt 2012; Deck et al. 2013). Both long and short time scales can be combined owing some modification of the AMD-stability criterion (Petit, Laskar & Boué, 2017). To take into account the chaos

induced by MMR overlap, we derive a general overlap criterion for first order MMR and we use it to improve the AMD-stability definition.

References:
Laskar, J. and Petit, A. C., 2017, AMD-stability and the classification of planetary systems, A & A, Volume 605, id.A72, 16 pp.
Petit, A. C., Laskar, J. and Boué, G., 2017, AMD-stability in presence of first order mean motion resonances, A & A, forthcoming ; https://arxiv.org/abs/1705.06756

54

A million-fold speedup in the dynamical characterization of multi-planet systems

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Many of the multi-planet systems discovered to date around other stars are maximally packed. This implies that simulations with masses or orbital parameters too far from the actual values will destabilize on short timescales; thus, long-term integrations allow one to constrain the orbital architectures of many closely packed multi-planet systems. This technique has yielded insights into several important systems, HR 8799, Kepler 11, TRAPPIST-1, and our own solar system. However, a central challenge in such studies is the large computational cost of N-body simulations, which preclude a full survey of the high-dimensional parameter space of orbital architectures allowed by observations.
I will present our recent success in speeding up this dynamical characterization by a factor of 1 million using machine learning. In particular, we generated a million-CPU-hour dataset of N-body simulations of tightly packed systems, and trained a gradient-boosted decision tree algorithm (XGBoost) to predict stability over billion-orbit timescales. By optimizing the features that we feed to the algorithm for each planetary system, we achieve a precision and recall of 90% on a holdout test set of N-body simulations from our dataset, as well as on N-body simulations of real Kepler systems.
This opens a wide discovery space for exoplanet characterization and planet formation studies as the next generation of spaceborne exoplanet surveys prepare for launch next year. I will discuss various applications, including maximizing the science output from the Transiting Exoplanet Survey Satellite (TESS), launching in 2018.

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Photometry of Proxima Centauri in Antarctica: A Candidate Transit Event of its Earth-size Planet

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Proxima˜Centauri is known as the closest star from the Sun. Recently, radial velocity observations revealed the existence of an Earth–mass planet around it. With an orbital period of 11 days, the surface of Proxima˜Centauri˜b is temperate and might be habitable. If the planet transits, it would be interesting to probe its radius, internal compositions and atmospheric properties. We took a photometric monitoring campaign of Proxima˜Centauri using the Bright Star Survey Telescope at the Zhongshan Station in Antarctica. A candidate transit event occurring on September 8th, 2016, is identified tentatively. Its transit epoch, T_C=2,457,640.1990±0.0017 HJD, is consistent with the predicted ephemeris based on

RV orbit in a 1 σ confidence interval. Time-correlated noise is pronounced in the light curve of Proxima˜Centauri, afflicting detection of transits. We develop a technique, in a Gaussian process framework, to gauge the statistical significance of potential transit detection. The candidate transit event reported in this work, has a confidence level of 2.5 σ. Kipping et al. (2017) reported two candidate transit events of Proxima˜Centauri˜b, observed by the Microvariability and Oscillation of Stars space Telescope in 2014 and 2015, respectively. However, the midtransit time of our detection is 138 minutes later than that predicted by their transit ephemeris. If all the transit events are real, the misalignment of the epochs plausibly suggests transit timing variations of Proxima˜Centauri˜b induced by an outer planet in this system. We plan to perform follow–up observation of Proxima˜Centauri in next Polar night at Dome A in Antarctica.

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The origin of the occurrence rate profile of gas giants inside 100 days

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We investigate the origin of the period distribution of giant planets. We fit the bias-corrected distribution of gas-giant planets inside 300 days found by Santerne et al. (2016) using a planet formation model based on pebble accretion. We investigate two possible initial conditions: a linear distribution of planetary seeds, and seeds injected exclusively on the water and CO icelines. Our simulations exclude the linear initial distribution of seeds with a high degree of confidence. Our bimodal model based on snowlines gives a more reasonable fit to the data, with the discrepancies reducing significantly if we assume the water snowline to be a factor of 3–10 less efficient at producing planets. This model moreover performs better on both the warm/hot Jupiters ratio and a Gaussian mixture model as comparison criteria. Our results hint that the gas-giant exoplanets population inside 300 days is more compatible with planets forming preferentially at special locations.

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Exoplanet Formation through the Eyes of Asteroseismology

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Asteroseismology is one of the most powerful tools to characterize the host stars and dynamical architectures of exoplanet systems, and has advanced our understanding of planet formation through intriguing discoveries such as the oldest known system of terrestrial planets (Kepler-444) and the only misaligned multiplanet system known to date (Kepler-56). In this talk I will present the latest results of our program to characterize exoplanets orbiting asteroseismic host stars using transits and radial velocities, including the discovery of a well-aligned warm Jupiter in an eccentric orbit and the confirmation of the closest known hot Jupiter orbiting an evolved star (KOI-4, Kepler's first exoplanet). I will furthermore present the latest results from our search for giant planets orbiting asteroseismic giant stars with the K2 mission, which has yielded first observational evidence that direct heating of planetary interiors is responsible for the radius inflation of hot Jupiters.

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An ALMA Survey of CO isotopologue emission from Protoplanetary Disks in Chamaeleon I

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The mass of a protoplanetary disk limits the formation and future growth of any planet. Masses of protoplanetary disks are usually calculated from measurements of the dust continuum emission by assuming an interstellar gas-to-dust ratio. To investigate the utility of CO as an alternate probe of disk mass, we use ALMA to survey ^{13}CO and C^{18}O J = $3-2$ line emission from a sample of 93 protoplanetary disks around stars and brown dwarfs with masses from 0.03 – 2 $M_\odot$ in the nearby Chamaeleon I star-forming region. We detect ^{13}CO emission from 17 sources and C^{18}O from only one source. Gas masses for disks are then estimated by comparing the CO line luminosities to results from published disk models that include CO freeze-out and isotope-selective photodissociation. Under the assumption of a typical ISM CO-to-H_2 ratios of 10^{-4}, the resulting gas masses are implausibly low, with an average gas mass of $\sim$ 0.05 M_{Jup} as inferred from the average flux of stacked ^{13}CO lines. The low gas masses and gas-to-dust ratios for Cha I disks are both consistent with similar results from disks in the Lupus star-forming region. The faint CO line emission may instead be explained if disks have much higher gas masses, but freeze-out of CO or complex C-bearing molecules is underestimated in disk models. The conversion of CO flux to CO gas mass also suffers from uncertainties in disk structures, which could affect gas temperatures. CO emission lines will only be a good tracer of the disk mass when models for C and CO depletion are confirmed to be accurate.

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A New Look at an Old Classic: Kepler-9's Obliquity, Masses, and Resonant Properties

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The Kepler-9 system harbors three known transiting planets, and was the first multi-planet system discovered using the transit method. It was also the first transiting system to display an orbital period ratio close to the 2:1 mean-motion commensurability. We report new assessments of the system, including (1) Rossiter-Mclaughlin (R-M) measurement of the projected spin-orbit angle for Kepler-9b, (2) accurate TTV-derived orbital elements (including planetary masses), and (3) a characterization of the resonant dynamics of the system.

Our R-M measurement for Kepler-9 system was the fourth such determination for a multi-planet system. All four cases show good spin-orbit alignments, with configurations that are similar to that of our Solar System, and which stand in contrast to many measurements of isolated hot Jupiters. We find that the outer two planets lie in the planetary mass "desert" that is generally associated with the rapid gas agglomeration phase of the core accretion process. Moreover, we find that the resonant arguments associated with 2:1 orbital commensurabilities (both eccentricity-type and mixed inclination-eccentricity type) all circulate. The planets' simultaneous presence in the mass gap, and absence from resonance provides a definite challenge to theoretical conjectures regarding how the system formed.

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Formation of Planetary Systems in Near Mean Motion Resonances

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The Kepler mission has released over 4496 planetary candidates, among which 3483 planets have been confirmed as of April 2017. The statistical results of the planets show that there are plenty of planet pairs in near mean motion resonances (MMRs). We proposed a formation scenario for the planetary configurations near 3:2 and 2:1 MMRs in terrestrial planetary systems. Firstly, low-mass planets form at a distant region; then they undergo type I migration until they reach the inner region of the gaseous disk. During the migration process, planets are trapped into MMRs. Planet pairs can departure from the exact location of MMRs due to the tidal interactions between the planets and the central star or the depletion of the gas disk. However, the mass accretion of planets and potential outward migration play an important

role in reshaping their final orbital configurations and increasing the possibility that planets are locked into 3:2 MMRs. Additionally, departure from the exact MMRs is an important process in the formation of planetary systems. We suggest that the depletion timescale of the gas disk play a crucial role in the process. If the eccentricity damping still strong enough after planets are captured into MMRs, the semi-major axis of the planet will change with the eccentricity damping leading to the formation of near MMRs configurations.

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Exactly how old is Moon?

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[1] *University of California at Davis*

Moon-forming giant impact likely represent the last major stage of terrestrial planet formation, followed by no more than ˜0.5% of additional accreted mass afterwards. It also provides a most convenient point in time to define the age of the Earth-Moon system because of its energy involved to reset isotopic clock in the major terrestrial and lunar reservoirs, namely silicate mantle and metallic cores. It is thus important to constrain the end stage of planetary formation in our solar system to bench mark protoplanetary disk evolution using the Earth-Moon system as the example. However, the exact age of Moon forming giant impact has been difficult to constrain for various reasons. In this talk, I will review progress made in the field of isotope cosmochemistry on this topic and the implications of the newly emerging data.

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Testing Grand Tack Model with Meteorites Isotopic Records

YIN, Qing-Zhu[1]

[1] *University of California at Davis*

There is an increasing number of isotope studies [1-6] that show solar system materials are divided into two main populations, one carbonaceous chondrite (CC)-like and the other is non-carbonecous (NC)-like, with minimal mixing attributed to a gap opened in the propoplanetary disk due to Jupiter's formation [5,7,8]. The Grand Tack model [9] suggests there should be large-scale mixing between S-, and C-type asteroids, an idea supported by our recent work on chondrule Δ17O-ε54Cr isotope systematics [10]. In this talk, I will present some of our recent work on this topic.

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Instability of mass transfer in a planet-star system

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Though constituting only a small fraction of the total exoplanet population, the close-in planets pose interesting challenges to theoretical models for the formation and evolution of planetary systems. Since the host stars generally rotate more slowly than the planet orbit, tidal interaction causes the planets to lose angular momentum. The planets on the closest observed orbits, on the order of a few days, would spiral into their host star within a few billion years. The final fate of spiral-in planets is still unclear, however. In this work, We investigate the instability of mass transfer between a Roche-lobe overflowing planet and its host star. We show that the angular momentum exchange mechanism governing the evolution of mass-transferring binary stars does not apply to Roche lobe filling planets, because most of the angular momentum of the mass-transferring stream is absorbed by the host star. Apart from a correction for the difference in specific angular momentum of the stream and the center of mass of the planet, the orbit does not expand much on Roche lobe overflow. We explore the conditions for dynamically unstable Roche lobe overflow as a function of planetary mass and mass and radius (age) of host star and equation of state of planet.

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High-resolution ALMA observations of gas and dust in protoplanetary disks

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While there is mounting observational evidence that complex dust substructures are common in protoplanetary disks, the distribution of molecular gas has not been as well-characterized. Yet, the molecular gas distribution is fundamental for governing how material from the disk is incorporated into forming planets. Due to its proximity and nearly face-on orientation, TW Hya is the best case study of protoplanetary disk structure. I will present deep ALMA observations of CO in the TW Hya disk at a spatial resolution of 8 AU, representing the most detailed look so far at molecular emission in a disk. The CO emission shows two prominent radial breaks, which radiative transfer modeling indicates can be reasonably reproduced by a steep decrease in the ^{12}CO column density at a radius of 15 AU, followed by a secondary peak at a radius of 70 AU. We propose that these features are a consequence of either CO depletion or gas density reductions affecting much of the vertical extent of the disk, and that either possibility would have significant implications for disk evolution. Finally, I will briefly discuss commonalities in dust and gas emission shared between TW Hya and other protoplanetary disks from our recent high angular resolution ALMA survey.

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STABILITY OF COPLANAR CIRCUMSTELLAR RETROGRADE ORBITS IN BINARY SYSTEMS

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We investigate the stability of coplanar circumstellar retrograde orbits in binary systems. Retrograde motions are rare but still are found in our own solar system, such as Triton and the irregular satellites of the giant planets, or suggested in exoplanet systems such as ν Octanis (Eberle & Cuntz 2010) and HD 59686 (Trifonov 2016). It is also well known that retrograde orbits are more stable than prograde orbits since Harrington (1977). Using numerical simulations we find the critical stability boundary in semi major axis $a_{\rm pl}$ of a retrograde test particle with initially circular orbit in various binary systems with different binary eccentricity ($e_{\rm b}$) and binary mass ratio (μ_2), with a resolution of $a_{\rm pl}$ = 0.0025$a_{\rm b}$ and integration time of 10^4 binary periods. We fit an empirical formula for a_c as a function of $e_{\rm b}$ and μ_2 , which is similar to the formula by Holman & Wiegert (1999) for the prograde case. By comparing the retrograde/prograde formulae we find the ratio of $a_{\rm c,retro}/a_{\rm c,pro}$ is roughly 1.6 over a large area in ($e_{\rm b}$, μ_2) parameter space, except in the region near the Hill's regime where the ratio approaches 2. In the Hill's regime we find that $a_{\rm c,retro}$ scales linearly with the Hill's radius, which is also found in the prograde case (Holman & Wiegert 1999) except that the scaling coefficients are different. Hamilton & Burns (1991) used generalized Hill's sphere to find the scaling coefficients to be 0.8 and 2.6 for prograde and retrograde orbits, but numerical simulations show that the coefficient should be 0.5 and 1.0. By accounting for the initially circular orbit becoming eccentric, we recover the 0.5 and 1.0 scaling coefficient values. This work is supported in part by Hong Kong RGC grant HKU 17305015.

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The dispersal of planet forming discs: a new generation of X-ray photoevaporation models

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The dispersal phase of planet forming disc strongly affects the formation and evolution of planetary systems. The prescription to model X-ray disc photoevaporation used in the last decade is based on fits to the hydrodynamical models by Owen et al. (2010). A major limitation of this approach was that the temperature prescription in the upper layers of the disc is a function only of the local density (through the ionization parameter). In this study, part of a new research network focused on transition discs, we improved these models by running a set of hydrodynamical simulation with the modern code PLUTO, where the temperature is a function not only of the local density but also of the column density. We provide several fits of the total mass-loss rate as a function of star's X-ray luminosity and disc cavity for transition discs which can be used as simple prescriptions in population synthesis models of planet formation, as well as line profiles produced within the wind for different inclinations. We find that the total mass-loss rate is increased by a factor 2 respect to the previous models and the X-ray photoevaporation can explain a larger fraction of observed transition discs. Although these differences are small, they can significantly impact planet formation (e.g. via streaming instability) and the final parking place of planets during their migration. We are expanding this study by probing also the effect of different stellar masses and an observed depletion in metallicity in the outer disc, which can help to rule out the unobserved population of disc relics.

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Formation of Close-in Earths and Super-Earths: Locating the MRI-Induced Pressure Barrier

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Earth, super-Earth and mini-Neptune sized planets are abundant on short orbits around solar and sub-solar mass stars. Could these planets form *in situ*? It has been proposed (e.g. Chatterjee & Tan 2014) that planets may form in a local gas pressure maximum that traps pebbles drifting radially towards the star due to gas drag. Such a pressure barrier is qualitatively expected at the outer boundary of the thermally ionized innermost disk, as the pseudo-viscosity induced by the magneto-rotational instability (MRI) decreases outwards. We determine the position and strength of the pressure barrier in steady-state disks, using an α-disk model in which the viscosity parameter α is *self-consistently* calculated from MRI criteria. Our earlier preliminary study of this (Mohanty et al. 2017) made a number of simplifying assumptions; here we present a significantly more realistic model: the disk vertical thermal structure is calculated from energy transport processes with self-consistent opacities, and the effects of chemistry on the MRI are included via both gas and dust phase chemical networks. The inferred radial location of the pressure barrier for various disk and stellar parameters is generally in agreement with the observed orbital radii of close-in planets. Such self-consistent and physically and chemically more realistic models of the disk structure allow us to test whether the MRI-induced pressure barrier can support *in situ* formation of small close-in planets; they also reveal various complexities in disk physics, relevant to planet formation, that have previously not been considered.

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Giant planet formation in the pebble accretion scenario

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Planetary growth can be greatly accelerated by the accretion of pebbles, which in contrast to planetesimals feel gas drag and drift inwards in the disc. As they approach the Hill sphere of a growing planet they can spiral down towards it and are accreted. However, as the planet grows, it pushes away material from its orbit due to the exchange of angular momentum. This allows the planet to open up a partial gap in the disc, generating a pressure bump outside of its orbit, which stops the inward flow of pebbles. The planet then has reached the so-called pebble isolation mass, at which pebble accretion stops. The planetary atmosphere is not bombarded by pebbles any more and can thus contract so that eventually a gas giant can form.
I will summarize the principle of pebble accretion and present new results regarding the pebble isolation mass and how sensitive it is on the disc's parameters (viscosity, H/r and background pressure profile). Equipped with this knowledge, I will discuss the different formation pathways of hot and cold Jupiters in evolving protoplanetary discs as a function of their formation location and disc metallicity.

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Rapidly rotating substellar objects

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Substellar objects such as exoplanets and brown dwarfs rotate and some of them have detectable rapid rotation. Recently, rotation velocities of exoplanets have been detected and their rotation velocities are higher than those of planets in the Solar system. Rotation period of brown dwarfs also have been detected and some brown dwarfs have clearly rapid rotation. Their minimum rotation periods are only a few hours and rotation velocities are much higher than those of planets in the Solar system. If the substellar objects have rapid rotation, their shapes might be largely deformed due to the strong centrifugal forces. Their structures cannot be well described by spherical models and so non-spherical models are required to describe them. In order to consider their evolution and structures, an 1D spherical model clearly becomes invalid. At least a 2D model is required to consider the evolution and structures of such rapidly rotating substellar objects. Almost all evolutionary code for substellar evolution, however, can treat only 1D models and nobody has succeeded in obtaining rapidly rotating 2D evolutionary models consistently. As a first step toward the rapidly rotating 2D models, we calculated quasi-evolutionary sequences of rapidly rotating substellar objects using both 1D evolutionary calculation by MESA and 2D rapidly rotating equilibrium calculation by our new numerical scheme (Fujisawa 2015). As a result, we have found that some young rapidly rotating substellar objects are spinning up due to the gravitational contraction as they cool. They might exceed critical rotation and break-up rotation velocity within a few 100 Myrs if the angular momentum is conserved during the evolution. Such rapidly rotating substellar objects would loss their angular momentum by wind or flare to avoid brake-up and the angular momentum loss timescale should be of a few Myrs.

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Changing perspective on planet formation

TRIAUD, Amaury[1]

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Many physical processes intermingle during planet assembly and during their subsequent orbital evolution. Very few observables provide an unambiguous view what results from planet formation. I will describe a new means to investigate the processes happening at formation, by changing perspective, by looking at the problem from a new vantage point. We will investigate planets away from single Sun-like stars, and observe what results from formation in systems are that different.
Physical processes are validated when they are tested over orders of magnitude. Thanks to discoveries like TRAPPIST-1 we can finally witness the outcome of planet formation in regimes that had remained unexplored before.
Directly matching the physical and orbital properties of planets orbiting single stars, to those of circumbinary planets has the potential to test what we think we know about planet formation. Given

time, I will describe my efforts to establish a systematic survey to seek circumbinary planets using ground-based facilities, including the results of a preliminary survey.

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Accreting Transition Discs with large cavities created by X-ray photoevaporation in C and O depleted discs

Author(s): Prof. ERCOLANO, Barbara[1]
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Circumstellar discs with large dust depleted cavities and vigorous accretion onto the central star are often considered signposts for (multiple) giant planet formation. In this poster we show that X-ray photoevaporation operating in discs with modest (factors 3-10) gas-phase depletion of Carbon and Oxygen at large radii (> 15 AU) yield the inner radius and accretion rates for most of the observed discs, without the need to invoke giant planet formation. We present one-dimensional viscous evolution models of discs affected by X-ray photoevaporation assuming moderate gas-phase depletion of Carbon and Oxygen, well within the range reported by recent observations. Our models use a simplified prescription for scaling the X-ray photoevaporation rates and profiles at different metallicity, and our quantitative result depends on this scaling. While more rigorous hydrodynamical modelling of mass loss profiles at low metallicities is required to constrain the observational parameter space that can be explained by our models, the general conclusion that metal sequestering at large radii may be responsible for the observed diversity of transition discs is shown to be robust. Gap opening by giant planet formation may still be responsible for a number of observed transition discs with large cavities and very high accretion rate.

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Observing the Evolution of Solids in Protoplanetary Disks

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The canonical model for the formation of terrestrial planets and giant planet cores relies on an early and very efficient phase of planetesimal growth in a gas-rich circumstellar disk. But, as theorists have known for decades now, there are some formidable obstacles to meeting that requirement. Many of these problems, and potentially their solutions, are associated with the growth and migration of "pebbles" (mm/cm-sized particles) in the first few million years of a disk's lifetime. That is fortuitous, since the continuum emission from these particles in nearby disks can be readily detected and resolved with long-baseline radio interferometers (e.g., ALMA, VLA). In this talk, I will describe what we are learning about the evolution of solids from such data, including: (1) the signatures of particle growth and migration; and (2) the mounting evidence that small-scale substructures in the (gas) disk play fundamental - and perhaps mandatory - roles in the planet formation process.

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The Critical Core Mass of Core Accretion Model for Planet Formation:the Effect of Mixing Length Theory

Author(s): LI, Sinan[1]
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In the standard calculation of planet envelope structure, the convection is usually assumed to be very efficient and the convective region is completely adiabatic. But this is not necessarily the case. Super-adiabatic regions would be formed in the convective region under certain circumstances. How do they

affect the critical core mass during the planet formation process still remains an open question. Here we investigate the effect of mixing length theory (MLT) on the structure of envelopes accumulated around protoplanetary cores for different planetesimal accretion rates. The outer boundaries of the envelopes are determined by the physical conditions within the protoplanetary disks (PPDs). We study the structure of the envelope for different locations within the PPDs as well. We show that the critical core mass, above which runaway accretion ensues, can be enhanced compared with the case that the MLT is not included. The super-adiabatic region would push the radiative-convective boundary (RCb) of the envelope outwards, leading to the increase of critical core mass. How the MLT affect the critical core mass depends sensitively on the planetesimal accretion rate and the physical conditions of PPDs where the core embedded.

74

Formation of TRAPPIST-1 and other low-mass planetary systems

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TRAPPIST-1 is a tiny, 0.08 solar-mass, M-star. Yet it hosts a planetary system comprising at least 7 (sub-)Earth planets, all residing within 0.1 au. I present a scenario for the formation of TRAPPIST-1 and other similar planetary systems. In our scenario we envision that planet formation commenced at the H2O iceline by streaming instabilities. Further growth proceeded by efficient accretion of mm to cm-size particles (pebbles) that drifted from the outer disk. This scenario has several advantages: it connects to the observation that disks are filled with pebble-size particles, it is efficient, it explains why the TRAPPIST-1 planets are ˜Earth mass, and it provides a rationale for the system's architecture. I will discuss new insights developed by our group on key processes that enter the model – e.g., the physics of the H2O ice line or pebble accretion efficiencies. I end with a discussion on how universal the ensuing planet formation paradigm could be.

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Migration of planets into and out of mean motion resonances in protoplanetary disks: the effect of nonlinear eccentricity damping

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[1] *Princeton University*

[2] *Cornell University*

[3] *Observatoire de Cote d'Azur*

A number of multiplanet systems are observed to contain planets very close to mean motion resonances, although there is no significnat pileup of precise resonance pairs. We present theoretical and numerical studies on the outcome of capture into first-order mean motion resonances (MMRs) using a parametrized planet migration model that takes into account nonlinear eccentricity damping due to planet-disk interaction. This parametrization is based on numerical hydrodynamical simulations and is more realistic than the simple linear parametrization widely used in similar studies. We find that nonlinear eccentricity damping can significnatly influence and the stability and outcome of resonance capture. In particular, the equilibrium eccentricity of the planet become larger, and this sometimes leads to ejection of the smaller planet. The captured MMR state tends to be more stable. In addition, when the migration is fast enough we observe a novel phenomenon of eccentricity overshoot which may help explain the lack of companion of hot Jupiters when compared to warm Jupiters.

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Photo-evaporation of protoplanetary disks in young open clusters

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During the evolution of proto-planetary disk, not only the viscosity, but also both central and external photo-evaporation play important roles. Considering a complicated radiation surroundings like the core of young open clusters or globular clusters, proto-planetary disk may not survive for a typical lifetime. In our model, we mainly focused on the disk around a TTS star, which encounters with another main-sequence star, the orbit parameters of the flyby will effect the evolution of the disk. Fixing other orbital parameters, small peri-center distance (d_{min}) of the flyby star may not accelerate the disk dispersion. There is a knee point d_0, where the flyby star can accelerated the disk evolution most obviously. Using the parameters of the Pleiades in which there are many B-type hot blue stars, the longevity of the disk will shrink to 1 Myr or even shorter. While using parameters of the out edge of the open young clusters, the flyby frequencies becomes smaller, and the lifetimes become typical values between 5 - 10 Myr. Finally we conclude that It's a possible mechanism resulting in different planetary formation rates in different radiation environments. The low formation rate of planets in GCs is also responsible for the null detection of planets around main sequence stars in GCs. Further more, our results induce that the planet detection is preferred in clusters without a dominated center sources, or clusters with small star densities.

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A GTC survey of transiting exoplanet atmospheres

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Thousands of exoplanets have been discovered in the past 20 years, showing a great diversity in physical parameters and architectures. Among them, hot gas giant exoplanets are the key targets that can potentially provide links to the planet formation and migration histories, because their atmospheres are hot enough to show spectral signatures arising from molecules composed of important elements (e.g. H, C, O, N, S). Recent studies have suggested that clouds and hazes are ubiquitous in exoplanet atmospheres, which would strongly weaken or even mute the spectral signatures especially when observing in the transit geometry. We have been carrying out a large systematic survey to characterize exoplanet atmospheres using transmission spectroscopy with the multi-object/long-slit (MOS/LS) optical spectrograph OSIRIS mounted at the 10.4 m Gran Telescopio Canarias (GTC). The optical transmission spectroscopy allows us to distinguish clear or hazy atmospheres from cloudy atmospheres, and to characterize the scattering or absorption signatures of atoms and molecules when detected. We have validated the technique of transmission spectroscopy by observing the atmosphere of a transiting white dwarf. Our survey has resulted in robust/tentative detection of alkali metals (Na, K), evidence of gaseous TiO/VO molecules, spectrally resolved Rayleigh scattering from hazes or H2 molecules, in several hot Jupiters and Neptunes. In this talk, we will present some of the latest results. We will discuss how we search for alkali metals as well as the presence of hazes or clouds. We will discuss the roles of instrumental systematics and stellar activity in shaping the transmission spectrum. With the recently commissioned near-infrared MOS/LS spectrograph EMIR and the blue sensitive CCD that will be soon installed on OSIRIS, we will discuss the contribution of GTC that could be complementary to the upcoming James-Webb space telescope.

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Existence, Frequency, and Detectability of Inclined and Non-Transiting Circumbinary Planets

HAGHIGHIPOUR, Nader[1]

[1] *Institute for Astronomy, University of Hawaii*

The success of the Kepler space telescope in detecting planets in circumbinary orbits has strongly indicated that planet formation around binary stars is robust and these systems may have planets of a variety of sizes and orbital configurations. A survey of the currently known circumbinary planets (CBPs) indicates that the orbits of many of these objects are slightly inclined and they precess with rates that place them out of transit for the majority of time. The latter strongly suggests that inclined and non-transiting circmbinary planets (CBPs) are common and the reason that not many of them have been discovered is that they did not transit during the primary mission of the Kepler telescope. This has raised many fundamental questions on the formation, dynamical evolution, long term stability, and ultimately the detectability of these objects. We have addressed these questions by carrying out a comprehensive 3D study of the post-formation evolution of CBPs and a detailed analysis of the orbital dynamics of these objects for different values of their inclinations as well as the binary orbital parameters and mass ratio. Results point to the existence of (3D) islands of stability where CBPs maintain stable orbits and never transit. We have determined the frequency of the existence of transiting and non-transiting CBPs for different parameters of the binary and orbital inclination of the planet, and have also derived, for the first time, empirical formulae for calculating the locations of 3D boundaries of stability. We have examined the possibility of the pile-up of CBPs near these (3D) stability boundaries and found that no such preference exists. Our study indicates that, consistent with observational results, majority of CBPs are in inclined and even non-transiting orbits, and that these orbits are the natural consequence of the post-formation evolution of these objects. We present details of our analysis and discuss their implications for the detection of inclined and non-transiting CBPs.

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Physical Mechanisms of Rossby Wave Instability and its Non-linear Outcome: Implicatons for Lopsided Structures in Protoplanetary Disks

Prof. MUTO, Takayuki[1]

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ALMA has discovered protoplanetary disks with lopsided structures, where dust particles are likely to accumulate. One of the possible mechanisms of the formation of such structures is the Rossby Wave Instability (RWI), which is a hydrodynamical instability that occurs when axisymmetric bump-like structures are present. Although the presence of such instability is known for decades, the exact conditions of the instability to occur and its physical mechanisms are not known until recently. We have performed systematic parameter search studies of linear perturbation analyses and non-linear hydrodynamical simulations to investigate the physics of the RWI and its non-linear outcome. We find the exact conditions for the onset of instability, which can be calculated semi-analytically when initial surface density and temperature profiles of the disk is provided. By investigating the eigenfunctions of linear perturbation analyses, we also find an intuitive explanations for the instability. With non-linear numerical calculations, we find characteristics of the lopsided structures produced by the RWI, which may be verified by future high resolution observations of gas in protoplanetary disks.
This presentation is based on the two papers following: T. Ono, T. Muto, T. Takeuchi and H. Nomura, ApJ, 823, 84 (2016) T. Ono, T. Muto, K. Tomida, and Z. Zhu, AAS Journals, submitted

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Ultra-Short Period Planets, Magnetospheric Truncation, and Tidal Inspiral

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Sub-Neptunes around FGKM dwarfs are evenly distributed in log period down to ~10 days but dwindle in number at shorter orbital periods. We demonstrate how magnetospheric truncation of disks and tidal inspiral of planets are responsible for sculpting this orbital architecture. Both the break at ~10 days and the slope of the occurrence rate down to ~1 day can be reproduced if planets form in disks that are truncated by their host star magnetospheres at co-rotation. Asynchronous tides raised in the star can transport planets from the disk inner edge to the shortest orbital periods (<1 day). Tidal migration can explain why these ultra-short period planets (USPs) are more widely spaced than their longer period

counterparts. We predict planet occurrence rates around A stars to also break at short periods, but at ~1 day instead of ~10 days.

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The Obliquity Variations of Habitable Zone Planets Kepler-62f and Kepler-186f

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Obliquity variations could play an important role in the climate and habitability of a planet. Orbital modulations caused by planetary companions and the planetary spin axis precession due to the torque from the host star may lead to resonant interactions and cause large amplitude obliquity variability. Here we explore the spin axis dynamics of two specific habitable zone exoplanets, Kepler-62f and Kepler-186f. Using N-body simulations and secular numerical integrations, we describe their obliquity evolution for particular realizations of the planetary systems. We then use a generalized analytic framework to characterize regions in parameter space where the obliquity is variable. We find that the locations of variability are fine-tuned over the planetary properties and system architecture in the lower obliquity regimes ($\lesssim 40^\circ$). As an example, the obliquities of both Kepler-62f and Kepler-186f are stable below~40◦, whereas the high obliquity regions ($\gtrsim 60^\circ$) allow moderate variabilities, assuming they areEarthanalogues. However, if the rotation period of Kepler-62f or Kepler-186f differs from Earth-like, thelower obliquity regions could become more variable. Extra undetected planetary companions and/orthe existence of a satellite could also destabilize the low obliquity regions. The variability amplitudesare very sensitive to even small increases ($\lesssim 3^\circ$) in mutual inclinations from coplanar configurations.We will show how to apply this analytical framework to devise guidelines for considering obliquityevolutions of exoplanets in general, which may have astrobiological implications.

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First results from CARMENES visual-channel radial-velocity measurements.

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We report new precise optical radial velocity (RV) measurements obtained with CARMENES for seven known M-dwarf planet hosts. These stars had been observed before with ultra-precise optical spectrographs such as HIRES and HARPS and were either reported to have one short period planetary companion (GJ\,15\,A, GJ\,176, GJ\,436, GJ\,536 and GJ\,1148) or are multiple planetary systems (GJ\,581 and GJ\,876). We aim at extending the baseline of observations for these stars and to quantify the performance of the CARMENES visual-channel in comparison with HARPS and HIRES. Our Doppler analysis of the combined HIRES, HARPS and CARMENES data uses by far the most complete set of high-precision RV data for these stars, allowing us to update the planetary orbital parameters and discover new planets in these systems. Based on our precise CARMENES data and the extended HIRES data we report the discovery of GJ\,1148 c, a second eccentric (e_c = $0.342^{+0.050}_{-0.062}$) Saturn-mass ($m_\mathrm{c}\sin i$ = $68.1^{+4.9}_{-2.2}$~$M_\oplus$) planet around GJ\,1148 with a period of P_c = $532.6^{+4.1}_{-2.5}$. We also report the discovery of another Saturn-mass ($m_\mathrm{c}\sin i$ = $51.8^{+5.5}_{-5.8}$~$M_\oplus$) planet GJ\,15\,Ac, which is currently the longest period planet around an M-dwarf star with a period of P_c = 7025^{+972}_{-629} days. In addition to these two new planet discoveries, we confirm the planets around all the investigated stars and we shed new light on their Keplerian orbits and dynamical properties. The only exception is GJ\,15\,Ab, for which we conclude that our precise CARMENES data and the post-discovery HIRES data show no evidence for the existence of the planet, which possibly leaves GJ\,15\,A only with the newly discovered planet c. Overall, our results demonstrate that the CARMENES optical RVs have a precision comparable to that of HARPS and are more precise than those of HIRES. We conclude that the CARMENES visual-channel is a state-of-the-art instrument, which is fully capable to discover potentially habitable rocky planets around low-mass stars.

83

Hot Jupiter Formation in Star-Disk-Binary Systems: Can Primordial Spin-Orbit Misalignment be Produced?

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Many hot Jupiter (HJ) systems have been observed to have their stellar equatorial plane misaligned with the planet's orbital plane. The origin of this spin-orbit misalignment and the formation mechanism of HJs remain poorly understood. A number of recent works have suggested that interactions between spinning stars, protoplanetary disks, and inclined binary companions may tilt the stellar spin axis with respect to the disk's angular angular momentum axis, producing planetary systems with misaligned planets. These previous works considered idealized disk evolution models and implicitly assumed that planets are always strongly coupled to the disk. In this paper, we explore how photoevaporation and the gravitational influence of planets formed close to their host stars affect the inclination evolution of planet-star-disk-binary systems. We find that the rapid depletion of the inner disk via photoevaporation reduces the excitation of stellar obliquities. Depending on the formation and migration history of HJs, the gravitational coupling between the stellar spin and the planet's orbit always reduces and may even completely suppress the excitation of stellar obliquities. In particular, we find that HJs formed in-situ experience negligible excitation of spin-orbit misalignment. Our work also constrains the migration hostory of HJs.

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Inclination Evolution of Protoplanetary Disks Around Eccentric Binaries

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It is usually thought that viscous torque works to align a circumbinary disk with the binary's orbital plane. However, recent numerical simulations suggest that the disk may evolve to a configuration perpendicular to the binary orbit ("polar alignment") if the binary is eccentric and the initial disk-binary inclination is sufficiently large. We carry out a theoretical study on the long-term evolution of inclined disks around eccentric binaries, calculating the disk warp profile and dissipative torque acting on the disk. For disks with aspect ratio H/r larger than the viscosity parameter α, bending wave propagation effectively makes the disk precess as a quasi-rigid body, while viscosity acts on the disk warp and twist to drive secular evolution of the disk-binary inclination. We derive a simple analytic criterion (in terms of the binary eccentricity and initial disk orientation) for the disk to evolve toward polar alignment with the eccentric binary. When the disk has a non-negligible angular momentum compared to the binary, the final "polar alignment" inclination angle is reduced from $90°$. For typical protoplanetary disk parameters, the timescale of the inclination evolution is shorter than the disk lifetime, suggesting that highly-inclined disks and planets may exist orbiting eccentric binaries

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Planet-disc interaction in laminar and turbulent discs

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A theory of planet formation should be able to explain the huge diversities of planetary systems discovered. In particular, the presence of gas giants poses a crucial constraint, given the short amount of time available to grow from μm dust particles to a fully fledged Jupiter-size planet before the star is

able to photoevaporate the gas component (within a few million years). Moreover, during this period of time, the planet migrates within the disc and interacts with its planetary system, potentially ending up accreted onto the star if other physical mechanisms do not intervene to stop this process. The leading theory of planet formation, the core accretion model, requires the formation of a several Earth mass core (where the exact value depends on the local properties of the disc) to initiate a rapid gas accretion process. We addressed this crucial initial phase by modelling a locally isothermal protoplanetary disc where a planetary core is embedded together with a swarm of solid particles from 0.1 mm up to 1 km in size and monitoring the solid accretion rate onto the core, for different initial masses. Furthermore, we tested the impact of a realistic implementation of gas turbulence (via the vertical shear instability - VSI). We found that small cores of 5, 10 Earth masses have a peak in the accretion rate for pebble-size particles while more massive cores (30, 100 Earth masses) are able to effectively filter them out halting this fast accretion pathway. Interestingly, the effect of the VSI on the solid component of the disc is negligible, leading to comparable accretion rates as for the laminar disc. However, the interaction between the small cores (5, 10 Earth masses) with the turbulent disc lead to an enhanced migration speed.

86

Exotic clouds in cold and hot planetary atmospheres

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Here "clouds" are broadly defined as suspended particles in planetary atmospheres. Haze particles are ubiquitous in all substantial atmospheres in the outer solar system. Abundant condensed particles are also inferred from the transmission observations in the warm and hot (500-2200 K) atmospheres of exoplanets which are hundreds to thousands degrees warmer than the solar system planets. From the thermodynamics point of view, those exotic clouds could result from condensation of salts, silicates and metals, and/or hydrocarbons produced by atmospheric chemistry. But the cloud origin, distribution, evolution and underlying physics are poorly understood. In this presentation, I will first talk about the thin, cold and hazy atmospheres in the outer solar system such as on Titan, Triton and Pluto. I will show how those atmospheres regulate themselves such that the chemical-produced hydrocarbon particles significantly dominate the radiative energy balance over the gas volatiles. This haze-control effect might help resolve some long-standing puzzles in explaining their atmospheric thermal structures. Then I will talk about the thick, hot and cloudy atmospheres such as the deep atmosphere of Jupiter and photospheres of hot Jupiters and brown dwarfs. I will show how to form clouds of salts, silicates and metals in this regime, highlighting the important physical processes such as seed formation, nucleation, condensation, gravitational settling as well as atmospheric particle transport. I will also show the importance of particle size distribution on interpreting the transmission spectra of exoplanets and how to predict it from the first principle in a self-consistent microphysical cloud formation model.

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Eccentric Warm Jupiters from Secular Interactions with Exterior Companions

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Recent studies suggest that most warm Jupiters (WJs, giant planets with semi-major axes in the range of 0.1-1 AU) probably form in-situ, or arrive in their observed orbits through disk migration. However, both in-situ formation and disk migration, in their simplest flavors, predict WJs to be in low-eccentricity orbits, in contradiction with many observed WJs that are moderately eccentric (e=0.2-0.7). This talk examines the possibility that the WJ eccentricities are raised by secular interactions with exterior giant planet companions, following in-situ formation or migration on a circular orbit. Eccentricity growth may arise from an inclined companion (through Lidov-Kozai cycles), or from an eccentric, nearly coplanar companion (through apsidal precession resonances). We quantify the necessary conditions (in terms of the eccentricity, semi-major axis and inclination) for external perturbers of various masses to raise the WJ eccentricity. We also consider the sample of eccentric WJs with detected outer companions, and for each system, identify the range of mutual inclinations needed to generate the observed eccentricity. For most systems, we find that relatively high inclinations (at least 40 degrees) are needed so that Lidov-Kozai cycles are induced; the observed outer companions are typically not sufficiently eccentric to generate the observed WJ eccentricity in a low-inclination configuration. These results place constraints on possibly unseen external companions to eccentric WJs. Observations that probe mutual inclinations of giant planet systems will help clarify the origin of eccentric WJs and the role of external companions.

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Impact of thermal diffusion and heat release on the orbital evolution of low-mass protoplanets

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Thermal diffusion affects the gravitational disturbance created in a gas by a point-like perturber and the back reaction of the gas on the perturber. We examine this effect in two different contexts: that of dynamical friction, in which a massive point-like perturber moves across a homogeneous medium at rest, and that of protoplanetary embryos embedded in a protoplanetary disc, where the strong Keplerian shear yields a markedly different response. At subsonic velocities, the main effect of thermal diffusion is the softening of the enthalpy peak that appears at the perturber's location. With respect to the adiabatic situation, the surroundings of the perturber are cooler and denser. Dynamical friction is enhanced by the dense region trailing the perturber, to the point that the force remains finite in the limit of a vanishing speed and has a value independent of the thermal diffusivity. In this limit, dynamical friction behaves much like "solid" or "dry" friction. In the Keplerian case, the overdensity resulting from thermal diffusion is sheared apart by the flow and gives rise to two dense lobes that drive a radial migration that can easily supersede the migration due to Lindblad and corotation torques for sub Earth-mass objects.
When, in addition to this, the perturber is luminous and releases heat in the surrounding gas, it triggers perturbations of opposite sign but similar to those considered above. When the luminosity is sufficiently high, the net force on a perturber in a medium at rest can be in the direction of motion rather than opposed to it, thereby speeding the perturber up rather than slowing it down. In the Keplerian case, migration can be directed outwards. More importantly, sufficiently luminous planetary embryos experience a growth of eccentricity and inclination to values comparable to the disc's aspect ratio, in sharp contrast with the conventional wisdom that the disc damps the eccentricity and inclination.

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Predicting planetary architectures via statistical mechanics

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The chaotic nature of planet dynamics in the solar system suggests the relevance of a statistical approach to planetary orbits. In such a statistical description, the time-dependent position and velocity of the planets are replaced by the probability density function (PDF) of their orbital elements. It is natural to set up this kind of approach in the framework of statistical mechanics. In this talk, I present a recent application of these ideas to the future planet orbits in the solar system (Mogavero 2017, A&A, 606, A79), aiming at reproducing the secular PDFs computed numerically by Laskar (2008, Icarus, 196, 1). I show that the microcanonical ensemble of the Laplace-Lagrange theory accurately reproduces the statistics of the giant planet orbits. To model the inner planets, I then investigate the ansatz of equiprobability in the phase space constrained by the secular integrals of motion, the angular momentum deficit in particular. The eccentricity and inclination PDFs of Earth and Venus are reproduced with no free parameters. Within the limitations of a stationary model, the predictions also show a reasonable agreement with

Mars PDFs and that of Mercury inclination, while the eccentricity of Mercury demands a deeper analysis. I finally discuss some current developments aiming at extending this analysis to the prediction of the PDF of the exoplanet semi-major axes. Such a statistical theory could be complementary to direct numerical simulations of planet trajectories in the study of planetary architectures.

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On the tiny friends of giant planets

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Jupiter and Saturn played important roles in sculpting the present day Solar System. Their interactions sent inward water-bearing asteroids, giving Earth its ocean. However, it is unclear if giant planets, in general, facilitate or inhibit the formation and prolonged existence of co-evolving small planets. Using Kepler data, we learned for the first time about preliminary occurrence rate constraints of super-Earth companions in giant planet systems. I will discuss what this result indicates the formation path of giant planets and their small planets. With the upcoming TESS mission surveying millions of bright stars in the sky, we will be able to discover and characterize many more systems hosting both giant planets and super-Earths. These systems will decode how the occurrence of super-Earth companions depend on the period of giant planets and advance our understanding of how the extrasolar giant planets act as architects of their own planetary systems.

91

Formation of wide-orbit gas giants near the stability limit in multi-stellar systems

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We have investigated the formation of a circumstellar wide-orbit gas giant planet in a multiple stellar system, focusing on orbital and mass evolution of a core of the giant planet that is scattered from an inner disk region by a more massive planet. We calculate the orbital circularization of the core associated with its growth in mass as it accretes the disk gas to become a gas giant, in which we took into account the effect of the tidal truncation radius of the protoplanetary gas disk by a binary companion. Since the scattered core accretes gas from the truncated disk, the disk truncation affects the orbital circularization process. The periastron distance is quickly lifted up while the apoastron distance shrinks. We found that the orbit after orbital circularization is usually close to the stability limit against the perturbations from the binary companion. As an example, we applied our model to a recently announced possible wide-orbit gas giant in a hierarchical triple system, HD131399Ab. The best-fit orbit of the planet is that with semimajor axis ~ 80 au and eccentricity ~ 0.35. Since the separation between the host star and a binary pair is ~ 350 au, the planetary orbit would be very close to the stability limit, which looks puzzling. However, with the original core location $\sim$ 20-30 au, the core (planet) mass $\sim 50 M_{\rm E}$ and the disk truncation radius ~ 150 au, our model shows that the orbital circularization through gas accretion until the final planet mass of $\sim 4 M_{\rm J}$ reproduces the best-fit orbit of HD131399Ab. Our conclusion that the orbits of circumsteller gas giant planets settle down near the stability limit can also be applied for wider or more compact binary systems if the separation is not too large and another planet with $>\sim$ 20-30 earth masses that scattered the core existed in inner region of the system.

92

The Architecture of Planetary Systems from Microlensing

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Current and future microlensing observations can detect dozens of (if not hundreds of) triple-object systems. So far there have been six such systems detected, including two multiple-planet systems and another four hierarchical triples (planets in binaries). Although microlensing can only measure the projected positions (rather than 3D positions) of the lens objects, we can constrain the 3D structure of these systems by combining the stability criterion and the a priori of some trivial parameters (e.g, inclination). Here I apply this method to some interesting systems, and present the results that we learn about the architectures of these systems as well as the outer planetary world in general.

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Early Science with the CHARIS High-Contrast Integral-Field Spectrograph

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I will present high-contrast exoplanet spectroscopy with the CHARIS integral-field spectrograph on the Subaru Telescope. CHARIS has completed its commissioning and has now obtained near-infrared spectra of a number of young exoplanets and brown dwarfs. The instrument implements a number of advances in its data analysis to gracefully handle saturation, suppress read noise, and deconvolve its spectra with the line-spread function. CHARIS also has a unique low-resolution mode that enables it to obtain R˜20 spectra simultaneously across the entire near-infrared from 1.15 to 2.35 microns. This spectral range makes CHARIS uniquely suited to spectral differential imaging and enables large improvements in contrast. I will present CHARIS spectra across the near infrared and discuss the prospects for retrievals of atmosphere properties. I will also briefly review plans for a CHARIS exoplanet survey targeting nearby young stars visible from the northern hemisphere.

94

Planet Eccentricity Sabotages Vortex Survival

Author(s): GU, Pin-Gao[1]
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We investigate the strength and lifetime of a vortex driven by a Jupiter-mass planet on a fixed eccentric orbit in a two-dimensional protoplanetary disk. We find that a planet-induced vortex becomes weakened and short-lived as the planet eccentricity increases. Our result may provide an implication relevant to various asymmetric contrasts in millimeter continuum emissions from transitional disks.

95

Interesting patterns in MMRs among adjacent planet pairs

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One of the most interesting topics about exoplanetary systems is to understand the history of planet formation and evolution. The Kepler space telescope has detected many exoplanets which revealed that multi-planet systems are common. In this work, we investigate the orbital configurations of multi-planet systems statistically. Our work focuses on the statistical characteristics of mean motion resonances (hereafter MMR) between adjacent planet pairs in multi-planet systems using the data from NASA official sites of Kepler telescope. We find that the MMRs are common and reveal some intriguing patterns in their distributions. These findings conflict with the general picture of in-situ formation scenario and may imply that some other mechanisms, e.g., migration, may play important roles in the history of planet formation and evolution.

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Automatic Analysis Tools for Stellar Parametrization and classification of cool stars

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With the ongoing/upcoming large ground and space-based surveys, such as Kepler mission, SDSS, LAMOST etc., large astronomical databases have become accessible in the real-time. But, growth in the data reduction and analysis sector does not match up well with the corresponding growth in data collection domain. However, automatic stellar parameter (Teff, logg and [Fe/H]) determination from low-resolution spectroscopy has seen some advancement in the past two decades. Automated algorithms for parameterization (or spectral classification) can be broadly put into two categories: Minimum distance methods (MDMs) and Non-linear regression methods. An example of each of these techniques, Full spectrum fitting and Artifical Neural Networking (ANN), would be discussed. Application of full spectrum fitting and determination of improved parameters for cool stars (later K and M type stars) will be presented in the presentation. Cool stars are the potential targets for searching the extraterrestrial life and studying chemo-dynamical evolution of the galaxy. Habitability of the planet is strongly influenced by the properties of its host star. Therefore the characterization of these stars is extremely crucial for exoplanetary and galactic studies.

97

Accreting Circumstellar and Circumplanetary Disks

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Recently commissioned telescopes and instruments (e.g., Subaru, GPI, VLA, ALMA, EVLA) are now finally able to resolve the protoplanetary disk down to the AU scale, and a rich variety of disk features have been revealed. To confront these observations, detailed protoplanetary disk models need to be developed. I will summarize our recent progress on constructing global 3-D MHD simulations of accretion disks to study accretion process and disk winds. To directly find young planets in protoplanetary disks, I will argue that accretion disks around the forming planets, so-called circumplanetary disks, could be the key and we may have already found some circumplanetary disk candidates. On the other hand, the accretion of these circumplanetary disks may be driven by the tidal torque from the host star, which is different form the accretion process in circumstellar disks. With more observations and theoretical developments, accretion disks around young stars and planets will be well constrained, providing a solid foundation for planet formation studies.

98

Interpreting HL-Tau In A Non Ideal Way

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Recent high resolution observations of HL Tau provides detailed structure of rings in its circumstellar disk. The origin of these rings has been widely investigated through different theoretical assumptions: snow lines, planet disk interactions, and gravitational instabilities of the disk itself. In this work we perform global 3D non-ideal MHD simulations with Athena++ to model the HL-Tau disk. The disk

ionization structure is provided by global dust evolution models. We take ambipolar diffusion as the major non-ideal MHD effect.

99

Comparing ALMA and VLT-SPHERE images of HD 135344B: different implications for potential planets

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In recent years, observations of transition disks in optical - near-infrared scattered light and (sub-)mm continuum emission have revealed complex structures such as spirals, rings and vortices. These are often interpreted as signs of ongoing planet formation, but so far no clear connection between the structures observed in scattered light and mm has been found. ALMA Cycle 1 Band 7 data of HD 135344B at 0.2" revealed new intriguing asymmetric dust structures in the disk but no spirals, in contrast with the VLT-SPHERE and NACO images clearly showing two symmetric spiral arms in the same object. These features make it an ideal and unique candidate to investigate the connection between the micron-sized dust distribution probed in scattered light and the mm-sized dust structures observed by ALMA. A new scenario has been presented in which the two spiral arms observed at scattered light originate from a single planet at ~30 au and from the secondary vortex at ~75 au rather than from a second planet further out as previously reported (van der Marel, Cazzoletti et al. 2016, ApJ 832, A178). We here present new ALMA Cycle 4 observations at 0.05" (PI Cazzoletti) which reveal the connection between micron and mm-sized dust in detail and allow us to test this scenario further.

100

Microphysical Kinetic Cloud Model in 1D Retrieval

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Clouds are notoriously hard to model, particularly in retrieval. Clouds play a critical role in planetary atmospheres, as they have a direct impact on the temperature and pressure structure, the total energy budget, and the observational properties of the planet. In retrieval, the inclusion of clouds is especially challenging, as it adds additional free parameters, overburdening already highly demanding computations and does not add much to the information criteria if the data are not of good quality. However, with the advent of new telescopes, particularly the James Web Space Telescope (JWST), our prognoses become more promising. JWST's high resolution and wavelength coverage will allow us to make more accurate constrains on the cloud properties like the cloud composition, particle size distribution, condensate mole fraction, cloud vertical extent and even partial cloud coverage. To date two main scenarios have been proposed to study the formation of clouds in exoplanetary atmospheres: (1) the equilibrium cloud formation scenario occurring upon vapor pressure saturation via vertical mixing and (2) the microphysical kinetic cloud scenario that accounts for the seed particles growth and transport. The microphysical cloud approach is considered more self-consistent, but also more challenging. It makes fewer assumptions regarding the formation of nuclei, a necessary starting point in formation of any condensate, and self-consistently follows the seed particle growth, sedimentation, evaporation, and vertical mixing. Here, we present the first implementation of the microphysical kinetic cloud model in retrieval and its application on the simulated JWST transit observations of HD 189733b.

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Gas dynamics of retrograde circumprimary disks in close binaries

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The gradual discovery of exoplanets in multiple star systems, especially in close binaries, has triggered investigations on planetary formation in binaries systems. Studies on both circumprimary and circumbinary disks are of great interest since the planetesimal accumulating in the early stage of planet formation is considered to be very sensitive to the perturbation of a secondary star. The formation of circumprimary planets in the binaries with orbital eccentricity is more challenging given the limited size and lifetime of the truncated disks (Artymowicz & Lubow 1994; Kraus et al. 2002). On the other hand, some work on circumbinary disks indicates that the tidal torque from an binary on the disk could be weaker in retrograde cases than that in prograde cases (Nixon & Lubow 2015). Since there are examples of likely retrograde circumprimary planets but most work on circumprimary disks has focused on prograde cases, here we explore the differences in response of the circumprimary disks under the perturbation of a close stellar companion in retrograde and prograde orbits with 2D hydrodynamical simulations for various binary mass ratios and eccentricities. Our simulations results suggest that the disk tends to be less affected in retrograde cases under some circumstances.
This work is supported in part by Hong Kong RGC grant HKU 17305015.

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Constraining Methane Abundance and Cloud Properties from the Reflected Light Spectra of Directly Imaged Exoplanets

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We have assembled an atmospheric retrieval package for the reflected light spectra of gas- and ice- giants in order to inform the design and estimate the scientific return of future space-based coronagraph instruments. Such instruments will have a working bandpass of ˜0.4-1 microns and a resolving power R˜70, and will enable the characterization of tens of exoplanets in the Solar neighborhood. The targets will be chosen form known RV giants, with estimated effective temperatures of ˜100-600 K and masses between 0.3 and 20 M_Jupiter. In this regime, both methane and clouds will have the largest effects on the observed spectra. Our retrieval code is the first to include cloud properties in the core set of parameters, along with methane abundance and surface gravity. We consider three possible cloud structure scenarios, with 0, 1 or 2 cloud layers, respectively. The best-fit parameters for a given model are determined using either a Monte Carlo Markov Chain ensemble sampler, or nested sampling. The most favored cloud structure is chosen by calculating the Bayes factors between different models. We are currently employing these tools to help define the technology requirements for the coronagraph instrument onboard WFIRST. I will present the results of our retrieval technique applied to a set of representative model spectra, and briefly review the relationship between the science return and instrument performance.

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Save the Planet, Feed the Star: Migration Feedback and Disk Accretion

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When planets migrate through disks, mass piles up ahead of them, generating a feedback torque that decelerates the migration. In low-to-no-viscosity disks, these gas pile-ups survive erosion and bring

planets to a full stop. Using hydrodynamical simulations running up to 10ˆ5 years, we investigate how and where planets park in gas-rich disks. We find that planetary cores above 10 Earth masses likely stall outside 1 AU: these may eventually nucleate into "cold Jupiters". Within inviscid disks, stalled planets also drive disk accretion at rates comparable to those observed. Families of super-Earths may be responsible for clearing the inner cavities of transition disks, shuttling gas either inward onto the host star, or outward to be blown away in a wind.

104

Dynamics of Circumstellar Planets in Binary Systems

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Radial velocity observations of the $1.9M_{\odot}$ K giant star HD 59686 have revealed a binary companion with a minimum mass of $0.53M_{\odot}$ in a moderately close ($a_B = 13.6$ AU) but highly eccentric ($e_B = 0.73$) orbit, as well as a planet with a minimum mass of $7M_{\mathrm{Jup}}$ orbiting the primary at $a = 1.09$ AU with $e = 0.05$. The best coplanar prograde fit is highly unstable, but there are nearby narrow regions of stable fits, with the planet locked in secular apsidal resonance with the secondary. Dynamical analysis shows that the best fit is outside the bulk stable region for nearly circular orbits, but that there are narrow regions of eccentric orbits beyond the bulk stable region stabilized by either secular apsidal resonance or mean-motion resonance. On the other hand, the orbit of the planet in HD 59686 is fully stable for a large range of orbital solutions, if it is nearly coplanar and retrograde. The implications for the formation of this planet will be discussed, as well as the evidence for another retrograde circumstellar planet in a binary system: nu Octantis.
This work is supported in part by Hong Kong RGC grant HKU 17305015.

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Viscously Unstable Inner Disks: A New In Situ Formation Mechanism for Close-in Earths and Super-Earths

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Currently, one of the more promising in situ mechanisms for building close-in small planets is the Inside-Out Planet Formation scenario (Chatterjee & Tan 2014), wherein inward drifting pebbles are trapped in an MRI-viscosity-driven pressure barrier in the inner disk. To investigate the formation and location of this pressure barrier, we have coupled the equations for the structure of an α-disk with the MHD criteria for efficient MRI, to derive the first steady-state α-disk solutions for the inner disk with a self-consistent MRI-driven α-viscosity. In so doing, we find that: (1) the surface density in the inner disk *decreases inwards* (a general feature of steady-state models with α increasing inwards due to thermal ionisation), and is thus much lower in this region than in the standard MMSN scenario; and (2) the inner disk is also viscously unstable ($\partial\Sigma/\partial\dot{M} < 0$), meaning that it tends to break up into rings. In combination, these two features provide a promising new in situ formation mechanism for multiple close-in small planets: (1) inward drifting dust grains will be trapped in such rings, to rapidly coalesce into planets; (2) multi-planet close-in systems, such as frequently observed, will be a natural outcome of multiple rings; and (3) the low *gas* surface density here provides a natural mechanism for avoiding the runaway growth of super-Earths cores into gas giants (a problem that has hindered previous in situ formation models in the inner disk; Lee, Chiang & Ormel 2014). We discuss this new formation mechanism, and further tests of and refinements to it.

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Exoplanets formation in near Mean Motion Resonances

JI, Jianghui[1]

[1] *Purple Mountain Observatory, Chinese Academy of Sciences*

Over 3600 exoplanets and 616 multiple planetary systems have been observed up to now. The planetary formation of the systems is an important problem. In this talk, we will introduce our recent studies on the planetary formation: (1)We use the planetary population synthesis model to study the planetary formation from planetesimals to the final planets with atmospheric evaporation included. We show that although the mass distribution of the planet populations is barely affected by evaporation, the radius distribution clearly shows a break at approximately two Earth radii and an "evaporation valley" appears at the planetary radius plane. (2)Using N-body simulation, we studied the formation of near mean motion resonances (MMRs) configurations. We suggested a formation scenario of such configuration. Planets can be trapped into MMRs during their orbital migration, the near MMRs configurations can be formed via the tidal effect or the eccentricity damping by the gas disk. And we found that the mass accretion process, the star accretion rate, and the speed of migration can have influence on the final configurations. According to our formation scenario, we can conclude that both type I and type II migration can play a crucial role in close-in terrestrial planet formation.

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Dynamical stability of the TRAPPIST-1 system

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TRAPPIST-1 is a system of seven roughly terrestrial-sized planets revolving on close-in orbits (within 0.06 AU) around a very low-mass M dwarf star (Gillon et al. 2017). All planets in this system are in or near mean-motion resonances (Luger et al. 2017), making this system the longest resonant chain system to be discovered. By computing the angular momentum deficit (AMD), we can assess whether the observed system is chaotic. We have examined the best-fit data from Wang et al. (2017) of the observed system, which are in 3-body resonances but not 2-body resonances initially. When integrating these nominal orbits, many of the systems are regular at the beginning but they subsequently make a transition to chaotic behaviour at different timescales, corresponding to when the systems break away from 3-body resonances. The variation of the system AMD is likely caused by chaotic variations in the semi-major axes due to overlap of 3-body resonances (Quillen 2011). In contrast, if we assemble the system into a resonant chain with 2-body resonances via convergent migration and integrate the orbits forward in time, the AMD of such a system does not exhibit any chaotic behaviour.
This work is supported in part by Hong Kong RGC grant HKU17305015.

108

On linear growth of streaming instability in pressure bumps

Dr. LAIBE, guillaume[1]

[1] *ens de lyon*

From previous studies, streaming instability may be expected to be ineffective in viscous discs, too efficient in inviscid discs, and to not operate in local pressure maxima where solids accumulate. By extending the current theory to the case of local pressure bumps, we aim to see if models of planet formation can be conciliated with recent observations of young discs.

109

Understanding planet formation through asteroseismology

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Often, the lack of accurate stellar parameters hampers our understanding of planet formation. Here, I present results from a *gold sample* of planet host stars with parameters determined through asteroseismology, and show how this provides key progress in understanding planet formation and architectures. For a sample of 117 planets, asteroseismology provided median uncertainties on the radius of 3.3%, enabling not only the detection, but also an interpretation of the radius valley. This valley is a bimodal distribution, with super-Earths ($\approx$ 1.5 $R_\oplus$) and sub-Neptunes ($\approx$ 2.5 $R_\oplus$) separated by a deficiency around 2 $R_\oplus$. For the first time, this sample allowed a measurement of the slope of the valley as a function of orbital period, which is consistent with models of photo-evaporation, but not with the late formation of rocky planets in a gas-poor environment. The exact location of the gap further points to planet cores consisting of a significant fraction of rocky material.
Furthermore, I will interpret the so-called Kepler dichotomy, using eccentricity measurements of small planets. Accurate mean stellar densities allow the determination of orbital eccentricities of small planets through transit durations. I show that multi-planet systems are nearly circular, in full agreement with solar system eccentricities, but in contrast to the eccentricity distributions previously derived for exoplanets from radial velocity studies. However, the systems with a single transiting planet have significantly higher eccentricities. I relate these findings to obliquity measurements for multi- and single-planet systems. Finally, I link these findings to planet formation and evolution theory and argue that the eccentricity of systems with a single transiting planet may be related to the presence of non-transiting planets on inclined orbits, but not to the presence of stellar companions.

110

L'-band Direct Imaging Search for Exoplanets Around Nearby Stars in Archival VLT/NACO Data

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We present preliminary results from a direct imaging search for exoplanets around nearby stars (< 15 pc) using L'-band archival data from VLT/NACO. Direct imaging is a powerful technique that samples a unique planet mass/separation parameter space and can therefore put complimentary constraints on giant planet formation and atmospheric models. L'-band (3.8 μm) high contrast imaging is sensitive to cooler and therefore older and/or less-massive planets compared to the 1 - 2.5 μm imaging employed by instruments such as VLT/SPHERE. We specifically target stars at distances less than 15 pc to search for planets with projected separations down to 1 - 5 AU from their host star, thus approaching with direct imaging the semi-major axes probed by long-term radial velocity monitoring campaigns. We apply the state-of-the-art principle component analysis pipeline PynPoint to archival L'-band data of nearby stars, such as τ Ceti, to improve the constraints on the giant planet population in these systems. These direct imaging results will ultimately be combined with the high-precision radial velocity detection technique to improve the census of exoplanets in the solar neighborhood.

111

Search for young planets in transition disks: investigating the early phases of planet formation with the Keck/NIRC2 vortex coronagraph.

REGGIANI, Maddalena[1]

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Protoplanetary disks with inner clearings, also known as transition disks, are the best laboratories for studying the early phases of planet formation. Cavities, asymmetries, and spiral structures could in fact be the signposts of young exoplanets interacting with the disk material. In the past two years, we took advantage of the vortex coronagraph installed on NIRC2 at the Keck telescope to look for young planets in several transition disks. I will summarize the main outcomes of the program, and describe how reference star differential imaging can overcome the shortcomings of angular differential imaging in detecting disk features. Finally, I will present in more details the case of the Herbig star MWC 758, where a protoplanet candidate has been detected.

112

Chaotic Growth and Dissipation of Dynamical Tides in Giant Planets Undergoing High-Eccentricity Migration: Formation of Hot and Warm Jupiters

Author(s): Ms. VICK, Michelle[1]
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[1] *Cornell University*

High-eccentricity migration is a possible mechanism for the formation of hot and warm Jupiters. In particular, the combination of Lidov-Kozai oscillation (where a giant planet is excited to a highly eccentric orbit driven by a distant planetary or stellar companion) and tidal friction has been shown to produce such systems on Gyr timescales, provided that efficient tidal dissipation operates in the planet. We re-examine this scenario with the inclusion of dynamical tides. When the planet's orbit is in a high-eccentricity phase, the tidal potential of the star can excite the oscillatory f-modes and r-modes in the planet. While the eccentricity remains large, the mode amplitudes can grow chaotically over multiple pericenter passages, drawing energy from the orbit and rapidly shrinking the semi-major axis. Eventually, the excited modes become too large and heat the planet as they dissipate non-linearly. We study the effect of this process on the planet's structure and orbit. We find that this pathway can produce hot Jupiters on a shorter timescale than previously suggested, and and in some cases creates eccentric warm Jupiters.

113

Avalanches in the AU Mic Debris Disk

Author(s): CHIANG, Eugene[1]
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[2] *University of California at Berkeley*

We solve the puzzle of the fast-moving, ripple-like features in the edge-on debris disk orbiting the young M dwarf AU Mic. The features are clouds of submicron dust repelled by the host star's wind. The clouds are produced by avalanches: radial outflows of dust that gain exponentially more mass as they shatter background disk particles in collisional chain reactions. The "avalanche zone" marks where the primary birth ring intersects a secondary ring of debris left by the catastrophic disruption of an asteroid-sized progenitor, less than tens of thousands of years ago. That disruptive micro-event opened a wound in the primary ring that is now hemorrhaging mass on macro-scales: avalanches can transfigure debris disks on timescales much shorter than the system age. We show that this picture works quantitatively, reproducing the masses, sizes, and velocities of the observed escaping clouds. The cloud trajectories are shaped by the wind's Lorentz forces and offer an unprecedented probe of stellar magnetic cycles—in this case of a pre-main-sequence star.

114

Studying the end stages of the protoplanetary disk phase

ESPAILLAT, Catherine[1]

[1] *Boston University*

Protoplanetary disks provide the reservoirs of gas and dust needed to form planets. Accordingly, the lifetimes of protoplanetary disks set the timescale for planet formation. The point at which a protoplanetary disk reaches the end of its lifetime and becomes a debris disk is difficult to identify. Here we discuss how we can better understand this evolutionary stage by focusing on objects that seem to "bridge" these two disk classes.

115

Characterizing the Coldest Exoplanets

Prof. SKEMER, Andy[1]

[1] *UC Santa Cruz*

Temperature, rather than mass, is the dominant factor in determining the appearance of gas-giant planets, and the diversity and complexity of worlds both increase at cold temperatures. The coldest known exoplanets are still much hotter than the gas giant planets in our own Solar System. Pushing to colder temperatures requires imaging in the thermal infrared (3-5 microns) where self-luminous gas-giants peak in brightness. I will present observational studies characterizing the atmospheres of the coldest exoplanets and brown dwarfs, down to a temperature of 250K. Additionally, I will describe some first results from ALES, a new instrument that can obtain thermal infrared spectroscopy of directly imaged planets for the first time.

116

Observational evidences of star-disk interaction on pre-main-sequence star

Mr. GUO, ZHEN[1]

[1] *KIAA, PKU*

Star-disk interactions are controlled by the stellar magnetosphere. Detections of brief extinction events are thought to indicate the presence of structures at the inner edge of the circumstellar disk created by these interactions. In long-term monitoring of the accreting T Tauri star GI Tau, we detect extinction events with typical depths of $\Delta V \sim 2.5$ mag that repeat quasi-periodically and stochastically and can last from days to months. A quasi-period of 18.4 days for extinctions over several months in 2014 - 2015 is the first empirical evidence of slow warps {\bf, which were temporary existed at a few stellar radii away from the central star under predictions by MHD simulations.} The reddening is consistent with $R_V = 3.85 \pm 0.5$ and, along with an absence of diffuse interstellar bands, indicates that some dust processing has occurred in the disk. The 2015 – 2016 multi-band lightcurve includes variations in spot coverage, extinction, and accretion, each of which result in different traces in color-magnitude diagrams. This lightcurve is initially dominated by a month-long extinction event and return to the unocculted brightness. The subsequent light-curve then features spot modulation with a 7.03 day period, punctuated by brief, randomly-spaced extinction events. The accretion rate measured from U-band photometry ranges from 5.2×10^{-8} to $1.7 \times 10^{-10} \mathrm{M}_\odot$ yr $^{-1}$, with an average of 4.7×10^{-9} $\mathrm{M}_\odot$ yr^{-1}. A total of 50\% of the mass is accreted during bursts of $> 12.8 \times 10^{-9}$ $\mathrm{M}_\odot$ yr^{-1}, which indicates limitations on analyses of disk evolution using single-epoch accretion rates.

117

A Search for Non-transiting Companions to Kepler Warm Jupiters: Clues to their Formation

MASUDA, Kento[1]

[1] *Princeton University*

We report the discovery of non-transiting companions to two transiting warm Jupiters on eccentric orbits, Kepler-448b and Kepler-693b, from the systematic search for transit timing variations in the Kepler data. The companions are found to be substellar or stellar mass objects, both on highly eccentric orbits with the periastron distances of 1.5au. Kepler-693b also exhibits a systematic drift in the transit duration, which points to a large (~50deg) misalignment between the orbits of the planet and the companion. While the companions can affect the orbital eccentricities of the inner planets on a secular timescale, the companions' small periastron distances argue against the tidal "high-eccentricity" migration of the inner planets from beyond 1au induced by these companions. Instead, these two systems suggest that even some of eccentric warm Jupiters arrived at the current short-period orbits via disk migration or were formed in situ, and that their eccentricities were excited later via interactions with a companion star/planet or gas disk.

118

The life of young planets in self-gravitating discs

STAMATELLOS, Dimitris[1]

[1] *University of Central Lancashire*

Gas giant planets may form early-on during the evolution of young protostellar discs, while these discs are relatively massive. I will present how Jupiter-mass planet-seeds evolve in self-gravitating discs using radiative hydrodynamic simulations that include radiative feedback from the planet itself. We find that the planet initially goes through a phase of rapid inward migration with quick mass and eccentricity growth, until it opens up a gap in the disc. Thereafter, the protoplanet either continues migrating inwards on a much longer timescale or starts migrating outwards. When the protoplanet resides in the warm inner disc region, or when radiative heating from the protoplanet heats its local surroundings, migration is inward. Outward migration occurs only when the protoplanet resides within a gap with gravitationally unstable edges. The effect of radiative heating from the protoplanet is critical in determining the direction of the migration and the eccentricity of the protoplanet. The fate of a planet-seed is diverse and could vary from a gas giant planet on a circular orbit near the central star to a brown-dwarf on an eccentric, wide orbit. We will place these results in the context of the observed properties of exoplanets.

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Validation of Planets from K2's Second Year

Author(s): LIVINGSTON, John[1]
Co-author(s): Dr. CROSSFIELD, Ian [2] ; Dr. PETIGURA, Erik [3] ; Ms. GONZALEZ, Erica [4] ; Dr. CIARDI, David [5] ; Dr. WERNER, Michael [6]

[1] *University of Tokyo*

[2] *MIT*

[3] *Caltech*

[4] *UCSC*

[5] *IPAC/Caltech*

[6] *JPL*

The NASA K2 mission has continued to yield large numbers of new planet discoveries in its second year. We have carried out a systematic program of transit detection and ground-based follow-up, resulting in a sample of well-vetted planet candidates. The K2 photometry along with constraints from follow-up spectroscopy and high resolution imaging have enabled us to statistically validate a large fraction of these systems. Of particular interest are a number of planets with bright host stars which are amenable to detailed characterization via radial velocity mass measurement and transmission spectroscopy, multi-planet systems, and small planets receiving Earth-like insolation. By conducting follow-up transit photometry with Spitzer, we have also refined the ephemerides of many interesting systems, which helps to ensure the feasibility of future atmospheric studies (i.e. with JWST).

120

Inward delivery of volatiles to inner planetary systems

WYATT, Mark[1]

[1] *University of Cambridge*

It is known that ˜20% of nearby stars host planetesimal belts orbiting 10s of au from the star. For a growing number CO gas has been detected coincident with the planetesimal belts showing that their planetesimals have a similar composition to Solar System comets. It is expected that some of these planetesimals may be perturbed into the inner regions of the system where they may collide with planets. The hot dust seen in several systems may be evidence of such comet-like dynamics, and in one system this picture is reinforced by the detection of CO close to the CO2 sublimation radius. This talk will present the evidence for the inward delivery of volatile material, as well as numerical simulations of the scattering process that determine the rate at which material is scattered in, as well as the effect this has on planetary atmospheres.

121

Dynamics and Transit Variations of Resonant Exoplanets

NESVORNY, David[1]

[1] *Southwest Research Institute*

The Transit Timing Variations (TTVs) are deviations of the measured mid-transit times from the exact periodicity. One of the most interesting causes of TTVs is the gravitational interaction between planets. Here we consider a case of two planets in a mean motion resonance (orbital periods in a ratio of small integers). This case is important because the resonant interaction can amplify the TTV effect and allow planets to be detected more easily. We develop an analytic model of the resonant dynamics valid for small orbital eccentricities and use it to derive the principal TTV terms. We find that a resonant system should show TTV terms with two basic periods (and their harmonics). The resonant TTV period is proportional (m/M*)^{-2/3}, where m and M_* are the planetary and stellar masses. For m=10^{-4} M*, for example, the TTV period exceeds the orbital period by ˜2 orders of magnitude. The amplitude of the resonant TTV terms scales linearly with the libration amplitude. The ratio of the TTV amplitudes of two resonant planets is inversely proportional to the ratio of their masses. These and other relationships obtained in this work can be used to aid the interpretation of TTV observations.

122

News from the world of stellar obliquities and orbital inclinations.

ALBRECHT, Simon[1]

[1] *Aarhus University*

I will present our recent results on the Tau Boo system, a wide binary hosting a hot Jupiter. The orbital inclination of Tau Boo Ab was measured by detecting the RV shifts of the planetary CO absorption line spectrum. We derive the orbital inclination of Tau Boo AB by combining 150 years of astrometric data with 20 years of high precision radial velocities. In the second part of my talk I will highlight some recent obliquity measurements and how they fit into the larger picture.

123

High-Contrast Imaging of Accelerating Stars from McDonald Observatory

BOWLER, Brendan[1]

[1] *University of Texas at Austin*

Long-baseline radial velocity planet surveys offer unique opportunities to measure the frequency, demographics, and architectures of giant planets in the outer regions of planetary systems. The McDonald Observatory Planet Search is one of the foundational RV planet surveys and has identified dozens of accelerating systems over the past two decades that indicate the presence of giant planets, brown dwarfs, or low-mass stars located on wide orbits of tens to hundreds of AU. I will present initial results from MASS— the McDonald Accelerating Stars Survey— a follow-up program which aims to uncover the nature of these companions through high-contrast adaptive optics imaging at Keck Observatory. In addition to the recovery of dozens of close stellar companions, orbit monitoring has yielded the dynamical mass of a late-T dwarf companion, enabling new tests of substellar evolutionary models approaching the planetary-mass regime.

124

Disks, Planet Formation, and the Structure of Planetary Systems

Author(s): MURRAY-CLAY, Ruth[1]
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[1] *University of California, Santa Cruz*

[2] *UCSC*

What sets the extent of giant planet formation, and what does this tell us about the structures of planetary systems in general? I will provide evidence that observed protoplanetary disks may be more massive than previously thought, show that gas turbulence coupled with pebble accretion may set the largest distances at which giant planets form, and discuss ways that we can use observations of wide-separation planets in concert with Kepler and radial velocity samples to constrain planet formation theories. Finally, I will comment on why Uranus and Neptune are not giants and discuss implications for the diversity of planetary systems.

125

Gas accretion onto giant planets

Author(s): LAMBRECHTS, Michiel[1]
Co-author(s): Dr. LEGA, Elena [2]

[1] *Lund University*

[2] *Nice Observatory*

Giant planets acquire significant gaseous envelopes within the approximately 3-Myr lifetime of protoplanetary discs around young stars. First, solid cores need to grow larger than several Earth masses, which is possible, even in wide orbits, by the efficient sweep-up of cm-sized pebbles. Subsequently, a gaseous envelope is accreted. In Lambrechts and Lega, 2017, we present 3D radiative hydrodynamical simulations to investigate the gaseous atmospheres around planets in the 5 to 15 Earth mass regime.These simulations show that the outer envelope is not in hydrostatic balance. Instead, gas from the disc is pushed through these outer layers in less than a 100 orbital timescales. This steady-state gas flow is important as it can prevent opacity-providing dust grains from raining out and it may reduce the cooling efficiency of the interior envelope. We found that the transition to runaway gas accretion, at the orbit of Jupiter, requires cores larger than about 15 Earth masses and disc opacities that are below 1 cm^2/g. When entering the runaway phase, new simulations show that gas accretion does not occur through dynamic infall, but instead continues to proceed through quasi-static contraction of the interior envelope. We will discuss the implications our work has on formation scenarios for giant planets, with specific attention to pollution of the envelope by the sublimation of accreted solids.

126

Cloud Atlas: A Comparative Study of Directly Imaged Planetary-Mass Companions with Hubble Space Telescope Time-resolved

Spectroscopy

ZHOU, Yifan[1]

[1] *University of Arizona*

The condensate clouds place an important challenge in understanding the ultra-cool atmospheres of exoplanets. The time-resolved observations of the cloud-induced rotational modulations provide direct and unambiguous constraints on the formation and properties of the clouds. I will report the latest HST/WFC3 IR light curves of two variable directly-imaged planetary mass/brown dwarf companions 2M1207b and HN Peg b as part of Cloud Atlas HST treasury program. We find spectral dependence of the rotational modulations especially for in- and out-of-water band, which allows us to infer the vertical cloud structures in these two ultra-cool low surface gravity atmospheres. We conduct a comparative study including these two objects as well as spectral-type matched variable brown dwarfs to evaluate the role of surface gravity in condensate cloud formations. This result highlights time-resolved observations that blossom in the brown dwarf studies making exciting contributions in characterizing exoplanets.

127

The gas and dust disk around the CQ Tau protostar

UBEIRA GABELLINI, Maria Giulia[1]

[1] *Università degli studi di Milano & European Southern Observatory*

We have studied the dust and gas distribution around a young (5Myr), nearby ($d = 160$ pc), intermediate mass (M=1.5M_{sun}) pre-main-sequence star, CQ Tau, using the Atacama Large Millimeter Array (ALMA) observations. Our focus is on finding the best representative model for the high-angular resolution observations of the protoplanetary disk around CQ Tau. In this system there is a clear evidence of the presence of an inner cavity in the disk dust distribution with an outer radius of 28 AU and there are evidences for ongoing planet formation. CQ tau is, then, the ideal candidate to try to distinguish between different clearing mechanisms of the disk cavity. In particular, we used the physical-chemical modeling tool DALI, that solves for the chemical structure, the radiative transfer and the thermal balance within the disk. Our data include the thermal continuum produced by cold dust, and line emission maps in different isotopologues of the CO molecule (^{12}CO, ^{13}CO and C^{18}O), that need to be considered simultaneously. We studied the distribution of three different profiles: gas, small dust grains (completely coupled with gas) and large dust grains (with a separate density distribution). The aim is to find constrains on the density properties and temperature of the cavity, in order to compare them with planet formation models.

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Implications of Exoplanet Microlensing for Planet Formation Theories

BENNETT, David[1]

[1] *NASA Goddard Space Flight Center*

Microlensing is able to detect planets orbiting beyond the snow line of their host stars. These orbits are beyond the reach of the transit method. Microlensing can find planets down to an Earth mass, which is much lower than can be probed by the Doppler radial velocity method in these orbits. Recent statistical analyses of planets found by microlensing indicate a planet population that is not consistent with the core accretion model predictions that come from population synthesis models. In particular, the microlensing results indicate that there is a large population of planets that seem to have undergone little net migration. Microlensing results also indicate a significant population of giant planets, intermediate in mass between gas and ice giants that are not predicted by current theories. Finally, I discuss how future microlensing analysis and observations from the WFIRST exoplanet microlensing survey will extend these results to give us a much more complete picture of all types of planets beyond the reach of transit surveys.

129

Unveiling the formation sites of directly imaged planets in scattered light

STOLKER, Tomas[1]

[1] *ETH Zurich*

The advent of extreme adaptive optics has provided a tremendous leap forward for spatially resolved observations of protoplanetary disks in scattered light. High-contrast imagers enable access to the formation sites of HR 8799-like systems by the detection of small dust grains beyond 5 au in the nearest star forming regions. A wealth of substructures and brightness asymmetries have been revealed in the surface layers of these disks which can be related to various processes, such as planet-disk interactions and dust evolution, that affect the distribution of the dust grains. I will highlight several of our investigations of protoplanetary disks around intermediate mass stars with the SPHERE instrument. We detected gapped disk structures, asymmetric shadows, and spiral density waves among others, yielding new insights into the shaping effect of potentially embedded planets, the warping of inner disk environments, as well as properties of dust grains in the disk surface. We discovered irregular shadowing variations on a timescale of days to weeks with multi-epoch imaging which we used as a unique diagnostic to probe the dynamical processes within 1 au. I will discuss the diversity of detected disk features in light of potentially forming planets but I will also point out the challenges that come with the interpretation of scattered light data sets.

130

Detectability of Vortices in Transition Disks

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There are many transition disks that have been observed to display significant azimuthal asymmetries in dust continuum, such as IRS 48, LkHα 330, HD 142527, etc. We investigate the influence of a massive planet in producing such asymmetries by carrying out 2D hydrodynamic simulations and 3D radiative transfer calculation. One primary goal is to determine the detectability of vortices in both gas and dust emissions. By using different ALMA configurations, we generate the synthetic ALMA images of these protoplanetary disk systems, including the gas moment maps. We find that the signatures of vortices in our simulated models can be detectable in certain ALMA configurations. Using IRS 48 disk as an example, we quantify the vortex signatures and describe the required ALMA configurations.

131

Accreting Circumbinary Disks: a Link Between Star and Planet Formation

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The binary fraction of Solar-type stars with periods of <100 days is nearly independent of age and environment, indicating that these binaries form early. The existence of gas disks around T-Tauri star binaries (e.g. DQ Tau, UZ Tau E) also tells us that binaries form (and perhaps migrate) well before these disks are dissipated. In addition, the detection of planets orbiting main sequence binaries of orbital periods <100 days reveals that circumbinary disks can form planets. Neverteless, it is still unclear how

the binaries themselves form and migrate, and how the perturbations they exert on their surrounding disks can alter the planet formation process. In this work, I describe a suite of direct hydrodynamical simulations of long-term accretion onto circular and eccentric T-Tauri stars using the moving-mesh code AREPO. I provide direct comparisons to observed pulsed/variable accretion onto known T-Tauri binaries, and describe how accretion variability depends on binary eccentricity. In particular, I compare simulation results to recent observations of the eccentric binaries DQ Tau and TWA 3A. Furthermore, I discuss the long-term consequences of circumbinary accretion, and their effect on the orbital elements of the binary, paying special attention to systemsthat result in outward migration. In addition, I will describe the excitation of eccentricity within the gas disk, and discuss how this can affect planet formation and growth.

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A Circumbinary Planet Orbiting A Pair of Active Stars

MILLS, Sean[1]

[1] *California Institute of Technology*

Approximately a dozen transiting circumbinary planets (CBPs) have been discovered to date. Here we report the characterization of KIC 10753734, a new addition to this collection. The system consists of a ˜0.1 Jupiter mass planet in a 254 day orbit around a 19 day binary pair of Sun-like stars. Unlike previous CBPs, in the KIC 10753734 system both stars of the binary show evidence of star spot activity and rotation. Conventional methods of decorrelating eclipse times with the local lightcurve slope to infer planetary mass are therefore insufficient. We describe a method to determine eclipse times by modeling star spots directly, the resulting inferences on planetary mass, and what can be learned about the stellar activity and rotation of the stars. We consider the usefulness of this characterization method for future space missions.

133

Dynamical evolution and stability maps of the Proxima Centauri system

MENG, Tong[1] ; JI, Jianghui[1] ; DONG, yao[None]

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The Proxima Centauri (Anglada-Escudé et al. 2016) was recently discovered to host an Earth-mass planet of Proxima b, further suggesting that there would be an additional planet of Proxima c with a 215 day orbit. In this work, we have investigated the dynamical evolution of the Proxima Centauri system with the full motion equations and semi-analytical models including relativistic and tidal effects via numerical simulations. We adopt the modified Lagrange-Laplace secular equations which consider two effects to study the evolution of orbital eccentricity of Proxima b, and find that the results are in good agreement with those of numerical simulations. The simulations show that relativistic effect has relatively large influence on the evolution of the eccentricity of two planetary orbits, and will restrain the eccentricity excitation of Proxima b, whereas the tidal effect plays a less important role in the eccentricity evolution of Proxima b within one million years.
Moreover, we also estimate the dynamical limits on orbital parameters that provide stable (quasi-periodic) motions of the Proxima Centauri system in the case of coplanar and non coplanar configurations with MEGNO technique. In coplanar case, we infer that the semi-major axis lies in the range from 0.02 au to 0.1 au, whereas the eccentricity is less than 0.4 for Proxima b, supporting the strong stable region. Additional simulations further show that the stable region for this system could exist for the eccentricity of Proxima b less than about 0.4 and that of Proxima c less than about 0.65. In non-coplanar case, mutual inclination angles of Proxima b and Proxima c are found to be lower than $50°$, which could provide stable (quasi-periodic) motions of the system.

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Dynamical Interaction between close-in Super Earths and their Magnetically Active Stars

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Some super Earths around magnetically active host stars have orbital periods less than a day. Analogous to the Jupiter-Io system, the planets' motion relative to the magnetosphere of their rotating host stars induces an electric field and generates a current across their diameter. It also excites Alfvin waves which propagate along the flux tubes connecting the planets and their host stars. The Lorentz torque associated with this circuit leads to planets' orbital evolution. We apply this method to infer the conductivity and composition of some planets' mantle based on the observational upper limit in the rate of their period change.

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Comparative Exoplanetology From Atmospheric Studies

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Exoplanet Atmospheres, Exoplanet Characterization.

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Direct imaging and spectroscopy of giant exoplanets: how and where to look?

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In this talk, I will first review the state of the art in direct imaging and spectroscopic characterization of giant exoplanets using ground-based adaptive optics systems. I will highlight recent high-impact scientific results and the techniques and technologies that enabled them. In the second part of this talk, I will present our recent result quantifying the occurrence rate of giant planets in dusty systems, demonstrating that debris disks are bona fide signposts to long-period giant planets. Finally, as a case in point, I will present the results of our new joint direct imaging and radial velocity study of the emblematic but curious case of the Epsilon Eridani planetary system.

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Joint growth of young star and protoplanetary disk

Dr. BAILLIE, Kevin[1]

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Most planetary formation simulations rely on simple protoplanetary disk models evolved from the usual, though inaccurate, Minimum Mass Solar Nebula. In this presentation, we suggest a consistent way of building a protoplanetary disk from the collapse of the molecular cloud. The novelty of our approach relies in the consistency of the {star + disk} model: both the central star and the disk are fed by the collapse and grow jointly. We then model the star physical characteristics based on pre-calculated stellar evolution models. After the collapse, when the cloud initial gas reservoir is empty, the further evolution of the disk and star is mainly driven by the disk viscous spreading, leading to radial structures in the disk: temperature plateaux at the sublimation lines of the dust species, shadowed regions that are

not irradiated by the star. These irregularities in the disk surface mass density or midplane temperature may help trap planetary embryos at these locations, eventually selecting the composition of the planet cores.
Here, we present the conclusions of our hydrodynamical simulations regarding the influence of the disk formation by the molecular cloud collapse on the trapping possibilities of protoplanets.

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Advection of Potential Temperature in the Atmosphere of Irradiated Exoplanets: A Robust Mechanism to Explain Radius Inflation

Dr. TREMBLIN, Pascal[1]

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The anomalously large radii of strongly irradiated exoplanets have remained a major puzzle in astronomy. Based on a two-dimensional steady-state atmospheric circulation model, the validity of which is assessed by comparison to three-dimensional calculations, we reveal a new mechanism, namely the advection of the potential temperature due to mass and longitudinal momentum conservation, a process occurring in the Earth' s atmosphere or oceans. In the deep atmosphere, the vanishing heating flux forces the atmospheric structure to converge to a hotter adiabat than the one obtained with 1D calculations, implying a larger radius for the planet. Not only do the calculations reproduce the observed radius of HD 209458b, but also reproduce the observed correlation between radius inflation and irradiation for transiting planets. Vertical advection of potential temperature induced by non-uniform atmospheric heating thus provides a robust mechanism to explain the inflated radii of irradiated hot Jupiters.

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The California-Kepler Survey

Dr. PETIGURA, Erik[1]

[1] *Caltech*

While Kepler has revealed over 4000 planets, key challenges to understanding their demographics are the often large uncertainties in host star properties. The California-Kepler Survey (CKS) is a large spectroscopic survey with the aim of bringing the properties of Kepler host stars into sharper focus. Using Keck/HIRES, we obtained high resolution (R=50,000), high SNR spectra of 1305 Kepler stars hosting over 2000 planet candidates. These spectra enable precise measurements of planet sizes, host star metallicity, and other quantities. I will give an overview of this survey and highlight key results, including the discovery of a gap in the size distribution of planets between Earth and Neptune size. This bimodality is likely the result of photo-evaporative sculpting.

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Secrets of giant planet formation: Massive HerbigAe discs

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Our recent survey of the gas and dust inventory in the discs of the Herbig Ae star population (1.5-3.5Msun, 5-10Myr) revealed overall high dust and gas masses. This is surprising considering that similar ALMA surveys of lower mass stars showed that protoplanetary discs are dispersed and giant planet formation halted by such advanced age of 5-10Myr. He hypothesize that the discs around the intermediate-mass stars follow a different evolution, in terms of their photoevaporation, temperature, and chemistry when compared to lower mass stars, causing longer lifetime of the disc mass reservoir as suggested by our ALMA data. This may explain why intermediate mass stars have the highest frequency of detected giant exoplanets. We present an overview of the current knowledge of the intermediate-mass pre-main sequence population as a whole and discuss how the challenges in characterising their disc evolution may be overcome with existing and upcoming telescopes, testing the above hypothesis.

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LAMOST Reveals Neptune-size Cousins of hot Jupiters, preferentially in "(metal-)rich" and "one-child" Kepler families

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We discover a new population of short-period, Neptune-size planets sharing key similarities with hot Jupiters: both populations are preferentially hosted by metal-rich stars, and both are preferentially found in Kepler systems with single transiting planets. We use accurate LAMOST DR4 stellar parameters for main-sequence stars to study the distributions of short-period (1d < P < 10d) Kepler planets as a function of host star metallicity. The radius distribution of planets around metal-rich stars is more "puffed up" as compared to that around metal-poor hosts. In two period-radius regimes, planets preferentially reside around metal-rich stars, while there are scantily any planets around metal-poor stars. One is the well-known hot Jupiters, and the other is a new population of Neptune-size planets (2 R_Earth < R_p < 6 R_Earth), dubbed as "Hoptunes". Also like hot Jupiters, Hoptunes occur more frequently in systems with single transiting planets than in multiple transiting planetary systems. About 1% of solar-type stars host "Hoptunes", and the frequencies of Hoptunes and hot Jupiters increase with consistent trends as a function of [Fe/H]. In the planet radius distribution, hot Jupiters and Hoptunes are separated by a "valley" at approximately Saturn size (in the range of 6 R_Earth <˜ R_p <˜ 10 R_Earth), and this "hot-Saturn valley" represents an approximately order-of-magnitude decrease in planet frequency compared to hot Jupiters and Hoptunes. The empirical "kinship" between Hoptunes and hot Jupiters suggests likely common processes (migration and/or formation) responsible for their existence.

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Mapping Substellar Evolution with Young Gas-Giant Planets and their Free-Floating Brown Dwarf Analogs

Prof. LIU, Michael[1]

[1] *University of Hawaii*

Direct detections of young gas-giant exoplanets and recent identification of young field brown dwarfs are strengthening the link between the exoplanet and brown dwarf populations. In particular, given the relatively small number of directly imaged planets and the modest associated datasets, the large census of young field brown dwarfs provides an indispensable foundation for understanding of both classes of objects, which overlap in their ages and masses.

We present results from a long-term comprehensive effort to measure physical properties of young ultracool objects using high-precision astrometry from the Hawaii Infrared Parallax Program. We map the influence of temperature and gravity from ˜100 Mjup to ˜5 Mjup. We show that young low-mass objects form a distinct sequence in color-magnitude diagrams, separate from the (old) field population. Current theoretical models are broadly consistent with this low-gravity sequence, though too blue and/or faint compared to the data. Surprisingly, we find that the low-gravity sequence for free-floating object and the locus of directly imaged companions may differ, suggesting the two populations may have different physical properties and/or evolutionary histories.

Finally, we show how high-precision dynamical mass measurements for brown dwarfs are beginning to test the fundamental theoretical models common to all studies of substellar objects.

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An opening criterion for dust gaps in protoplanetary discs

Dr. DIPIERRO, Giovanni[1]

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Recent spectacular spatially resolved observations of gaps and ring-like structures in nearby dusty protoplanetary discs have revived interest in studying gap-opening mechanisms. In this talk I'll describe the two distinct physical mechanisms for dust gap opening by embedded planets in protoplanetary discs: I) A mechanism where low mass planets, that do not disturb the gas, open gaps in dust by tidal torques assisted by drag in the inner disc, but resisted by drag in the outer disc; and II) The usual, drag assisted, mechanism where higher mass planets create pressure maxima in the gas disc which the drag torque then acts to evacuate further in the dust.
Starting from numerical evidences, we derive a grain size-dependent criterion for dust gap opening in viscous protoplanetary discs by revisiting the theory of dust drift to include disc-planet tidal interactions and viscous forces. From this formalism, we derive i) a grain size-dependent criterion for dust gap opening in discs, ii) an estimate of the location of the outer edge of the dust gap and iii) an estimate of the minimum Stokes number above which low-mass planets are able to carve gaps in the dust only. These analytical estimates are particularly helpful to appraise the minimum mass of an hypothetical planet carving gaps in discs observed at long wavelengths and high resolution. We validate the theory against 3D SPH simulations of a broad range of dusty discs hosting an embedded planet. We find a remarkable agreement between the theoretical model and the numerical experiments.

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How planetary systems are shaped by their birth environments in star clusters?

Dr. CAI, Maxwell Xu[1]

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The star formation process occurs in star clusters and stellar associations, following the collapse of the giant molecular cloud. As a byproduct, planets form in protoplanetary disk within 10 Myr after the star formation process. Before the dissolution of the parental cluster, planetary systems are exposed in a high stellar density environment, subject to frequent perturbations from stellar encounters, which in turn lead to the excitation of orbital eccentricities and inclinations, and also planet ejections. The memory of orbital eccentricity/inclination excitation can be preserved long after the dissolution of the parental cluster, and therefore field planetary systems may bear signatures from their parental clusters. In this talk, I will present several signatures of parental clusters on field planetary systems from numerical simulations. These signatures provide useful clues to constrain the birth environment of the field planetary systems, including our Solar System. I will also show that the diversity of exoplanets may be a consequence of their early evolution in star clusters.

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Inside-Out Planet Formation

Prof. TAN, Jonathan[1]

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The Kepler-discovered systems with tightly-packed inner planets (STIPs), typically with several planets of Earth to super-Earth masses on well-aligned, sub-AU orbits may host the most common type of planets in the Galaxy. They pose a great challenge for planet formation theories, which fall into two broad classes: (1) formation in the outer disk followed by inward migration; (2) formation in situ. I review the pros and cons of these classes, before focusing on a new theory of sequential in situ formation from the inside-out via creation of successive gravitationally unstable rings fed from a continuous stream of small (˜cm-m size) "pebbles," drifting inward via gas drag. Pebbles first collect at the pressure trap associated with the transition from a magnetorotational instability (MRI)-inactive ("dead zone") region

to an inner MRI-active zone. A pebble ring builds up until it either becomes gravitationally unstable to form an Earth to super-Earth-mass planet directly or induces gradual planet formation via core accretion. The planet continues to accrete until it becomes massive enough to isolate itself from the accretion flow via gap opening. The process repeats with a new pebble ring gathering at the new pressure maximum associated with the retreating dead-zone boundary. I discuss the theory's predictions for planetary masses, relative mass scalings with orbital radius, and minimum orbital separations, and their comparison with observed systems. Finally I speculate about potential causes of diversity of planetary system architectures, i.e. STIPs versus Solar System analogs.

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Orbital Architecture of Close-in Planetary Systems Formed by Giant Impacts

Prof. KOKUBO, Eiichiro[1]

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We investigate the in-situ formation of close-in terrestrial planets including super-Earths by giant impacts using N-body simulations. The goal of this study is to obtain the basic scaling laws of close-in terrestrial planet formation as a function of properties of protoplanet systems. We systematically change the system parameters of initial protoplanet systems and investigate their effects on final planetary systems. We find that in general non-resonant dynamically cold compact systems are formed. The orbits of planets are less eccentric and inclined and the orbital separations of adjacent planets are smaller, compared with those formed in the outer disk. These properties are natural outcomes of giant impacts in the inner disk. In the inner disk the ratio of the physical radius to the Hill radius is large, in other words, gravitational scattering is relatively less effective compared with that in the outer disk. Thus protoplanets are less mobile and accretion proceeds relatively locally, which leads to formation of dynamically cold compact systems.

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The observational signals of exoplanets' atmospheric escape

Ms. YAN, Dongdong[1]

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Atmospheric escape of exoplanets has be detected in hot-Jupiter HD 209458b, HD 189733b and warm-Neptune GJ 436b. Observations show extra Lyman-α(Lyα), Hα and Balmer jump and continuum absorption in such planetary systems, which indicate that these planets are undergoing atmospheric escape beyond their Roche Lobes. Up to now, tremendous exoplanets have been discovered. However, only a few of them have been detected experiencing atmospheric escape and the escape signals are not fully studied. In this paper, we present a radiative transfer simulation to evaluate the absorption signals of Lyα, Hα and Balmer jump and continuum for 34 planetary samples. Among our simulation results, most hot Jupiters, Neptunes and Saturns have strong obervable Lyα and weak Hα absorption signals. Super-Earths and Earth-like plantes tend to have weak Lyα absorption and no Hα absorption signatures are found in most earth-sized planets. Besides, no signals of Balmer jump and continuum absorption are found in our simulations. Our results show that the observations of Far-UV are most important for discovering the escape of atmosphere. The signals in optical band may seem not very remarkable due to the scanty number density of atomic hydrogen in n=2 level.

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Evidence of differential rotation inside Saturn from waves of its rings

Dr. MOUTAMID, Maryame El[1]

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We report in this paper observational evidence of Saturn's differential rotation rate from analysis of its main rings, using data that come from the Visible and Infrared Mapping Spectrometer (VIMS) instrument on board the Cassini spacecraft.
The average rotation of Saturn has been estimated by many authors based on different analyses of its gravitational field and its shape (Anderson et al., 2007, Read et al., 2009, Helled et al., 2015). However it still unclear what is the right averaged value. Moreover, no work has been done so far to investigate its differential rotation.
In addition to the work that has been done by Hedman et al., (2009), Hedman et al., (2014), El Moutamid et al., (2016) who found several waves that have pattern speed consistent with the expected range of Saturn's rotation rate, we analyzed all the main rings and found other waves that seem to match with the right number of resonance and around the expected pattern speed.
The physical interpretation of our results that we provide is these low-amplitude density waves are generated by many density anomalies, located at different radii inside the planet, rotating within different pattern speed, suggesting that Saturn has an internal differential rotation of about 5%.

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Physical processes in the interior and the atmosphere of (solar and extrasolar) giant planets

Prof. CHABRIER, Gilles[1]

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The conventional description of the atmosphere and the interior of giant planets relies on two pilars: (1) cloud formation near the photosphere is responsible for their spectral energy distribution, (2) the interior of the planet is homogeneous and heat is transported by large-scale adiabatic convection. In this talk, I will show that such a picture is likely to be too simplistic and that more subtle physical mechanisms might be taking place in the atmosphere and the interior of these bodies. This could change drastically our present understanding of the structure and the evolution of giant solar and extrasolar giant planets.

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Exoplanet Masses and Radii – An Update from K2 and a NASA-Keck Key Project

Prof. HOWARD, Andrew[1]

[1] *California Institute of Technology*

We present results from a NASA Keck Key Project to measure the masses of small planets from the K2 Mission using Keck/HIRES. This project explores the compositional diversity of planets between the size of Earth and Neptune and identifies suitable targets for atmospheric study by JWST. To date, we have measured the masses and densities of more than 20 sub-Neptune-size planets, significantly expanding on the mass/radius measurements from Kepler. Our measurements help to map out the transition from rocky to gas-dominated planets with higher fidelity and probe the dependence of planet composition on planet radius, incident flux, host star properties, and system architecture, connecting bulk planet composition with planet formation and evolution.

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Time Domain Observotory of Nanjing University and our related works

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Here I will report of progress of on-going project: time domain observatory (TiDO) of nanjing University in Ali, Tibet (5100 m high), which includes of three 30-cm (each with FOV 64 square degrees), one 18-cm (FOV 144 square degrees), and a 1-m telecopes(9 square degrees). The small telecope array will be ready by the end of this year. TiDO is designed mainly for exoplanet transting survey, and I will report our plan for future exoplanet survey. Also I will report one of our recently work on the formation of metal pollutions in photospheres and dusty disk around white dwarfs in an evolutional scenario, which explains qulitatively the relative possess rate between metal pollutions and dusty disk.

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Inferring Masses and Eccentricities from Transit Time Variations: Modal Decomposition and Geometric Interpretation

Prof. SARI, Re'em[1]

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We lay out a simple procedure for inferring masses and eccentricities for systems containing two planets where both planets are observed to transit. We abandon expansion around resonances. Instead, we use a small set of numerical integrations to decompose the possible perturbations into three modes. One related to the mass of the perturber while the other two correspond to the two components of the relative eccentricities. We provide a simple geometric interpretation of these three modes, and demonstrate our method on several systems in Kepler's data.