2022 DDA Meeting Abstract Book

Monday April 25

Session: Disequilibrium in the Galactic Disk

A Milky Way in motion: Dealing with dynamical disequilibria

Jason Hunt[1], Kathryn Johnston[2], Elise Darragh-Ford[3], Adrian Price-Whelan[4], Suroor Gandhi[2]
[1]Centre for Computational Astrophysics, Flatiron Institute, New York, NY, [2]Columbia University, New York, NY, [3]Stanford University, Stanford, CA, [4]Flatiron Institute, New York, NY

Data from ESA's Gaia mission is already revolutionizing Galactic astronomy, providing an unprecedented view of the Solar neighborhood and beyond. However, while it provides us a great opportunity to transform our understanding of the Milky Way, it has also highlighted how far from equilibrium our Galaxy is. The spiral pattern in vertical position vs. velocity is a signature of our Galaxy's past interaction with perturbing influences such as merging dwarf galaxies. We dissect and analyze these spirals, and show how we can leverage high resolution galaxy models and dynamical theory to learn about the structure and history of our Galaxy.

Phase-space spirals as probes of perturbed, out-of-equilibrium disk galaxies

Uddipan Banik[1], Martin Weinberg[2], Frank Van Den Bosch[1]
[1]Yale University, New Haven, CT, [2]University of Massachusetts, Amherst, Amherst, MA

Disk galaxies are highly responsive systems that undergo oscillations triggered by various agents such as external forces and tides from satellite galaxies and dark matter substructure. Such gravitational interactions tend to throw disk galaxies out of equilibrium. In due course, stellar oscillations lose coherence and perturbations damp out by collisionless relaxation mechanisms like phase-mixing and Landau damping, which manifest as phase-space spirals. These dynamical features have recently been observed by GAIA in our Milky Way galaxy, hinting at the possibility of recent interactions in the galactic disk. In this talk I shall demonstrate a general perturbative formalism to compute the disk response to various perturbers such as spiral arms and satellite galaxies and obtain the resultant phase-space spirals. Using this formalism, I shall elucidate the perturber characteristics responsible for triggering bending and breathing oscillation modes corresponding to one- and two-armed phase-space spirals. This can be used to constrain the Milky Way's dynamical history. I shall also discuss the survivability and observability of phase-space spirals in the galactic disk, and illustrate their usefulness as probes of the galactic potential.

Stellar Migration in the Milky Way's Disc from Encounters with the Sagittarius Dwarf Galaxy

Christopher Carr[1], Kathryn V. Johnston[1]
[1]Columbia University, New York, NY

Stars born on near-circular orbits in spiral galaxies can subsequently migrate to different orbits due to interactions with non-axisymmetric disturbances within the disc such as bars or spiral arms. In this talk I will discuss the role of external influences on radial migration using the example of the interaction of the Sagittarius dwarf galaxy (Sgr) with the Milky Way (MW). To understand this effect, we used a collisionless N-body simulation of a Sgr-like satellite interacting with a MW-like galaxy. For my talk I will show how tidal forcing from Sgr can produce changes in angular momentum and eccentricity of stellar orbits, and how the combination of this dynamical signature with other stellar observables like metallicity, may be used to distinguish between the different migration mechanisms shaping the chemical abundance patterns of the Milky Way's thin disc.

Evidence of a vertical kinematic oscillation beyond the Radcliffe Wave

Lekshmi Thulasidharan[1], Elena D'Onghia[1], Eloisa Poggio[2,3], Ronald Drimmel[2], John Gallagher[1], Cameren Swiggum[4], Robert Benjamin[5], Joao Alves[6]
[1]University of Wisconsin Madison, Madison, WI, [2]INAF - Osservatorio Astrofisico di Torino, Pino Torinese, [3]Université Còte d'Azur, Nice, [4]University of Vienna, Vienna, [5]University of Wisconsin, Whitewater, Whitewater, WI, [6]ESO, Garching

The Radcliffe Wave (RW) is a recently discovered sinusoidal vertical feature of dense gas in the proximity of the Sun. In the disk plane, it is aligned with the Local Arm. However, the origin of its vertical undulation is still unknown. This study constrains the kinematics of the RW, using young stars and open clusters as tracers, and explores the possibility of this oscillation being part of a more extended vertical mode. We study the median vertical velocity trends of the young stars and clusters along with the RW and extend it further to the region beyond it. We discover a kinematic wave in the Galaxy, distinct from the warp, with the amplitude of oscillation depending on the age of the stellar population. We perform a similar analysis in the N-body simulation of a satellite as massive as the Sagittarius dwarf galaxy impacting the galactic disk. When projected in the plane, the spiral density wave induced by the satellite impact is aligned with the RW, suggesting that both may be the response of the disk to an external perturbation. However, the observed kinematic wave is misaligned. It appears as a kinematic wave travelling radially, winding up faster than the density wave matched by the RW, questioning its origin. If a satellite galaxy is responsible for this kinematic wave, we predict the existence of a vertical velocity dipole that should form across the disk, and this may be measurable with the upcoming Gaia DR3 and DR4.

Building an Acceleration Ladder with Tidal Streams and Pulsar Timing

Peter Craig[1], Sukanya Chakrabarti[2], Robyn Sanderson[3], Farnik Nikhathar[3], Stella Reino[4]
[1]Rochester Institute of Technology, Rochester, NY, [2]Institute of Advanced Study, Princeton, NJ, [3]University of Pennsylvania, Philadelphia, PA, [4]Leiden University, Leiden

We analyze stellar streams in action-angle coordinates combined with local acceleration measurements to provide joint constraints on the potential of the Milky Way (MW). The stream methodology uses a combination of the Kullback-Liebler divergence (KLD) and likelihoods calculated using the two-point correlation function. Accurate potential models are expected to produce highly clustered actions for the stream members. The KLD is used for measuring the clustering of a set of actions, while the likelihoods are calculated for combining methods and estimating the uncertainties on our potential parameter estimates. We use Fisher matrix analysis to combine the local measurements with the stream results and to perform our error analysis. This work can be thought of as an "acceleration ladder", where direct local measurements that are currently limited to the solar neighborhood are combined with indirect techniques that can access a much larger area of the MW. We consider the Nyx, Palomar 5, Orphan, GD1 and Helmi streams in our analysis. This combination of streams features spatial overlap with the local measurements from the Nyx stream and extends to other areas of the Galaxy using the other streams. Utilizing this data we then constrain several common models for the MW potential. In addition to typical MW potential models, we also include a model used with the local measurements, which was found to provide a good fit to the direct acceleration data.

Session: Star Clusters

Modeling open clusters in the CMD: binaries, mass function, and dynamical evolution

Lu Li[1]

[1]Shanghai Astronomical Observatory, Chinese Academy of Sciences, Shanghai

As cradles of stars and building blocks of galaxies, open clusters (OCs) encode valuable information about star formation and galaxy evolution. Therefore, precisely and robustly measuring the fundamental properties of OCs, including age, metallicity, distance, extinction, stellar mass function (MF), and binary properties, is of great importance. The field star contamination has long been a major obstacle. Here I will present a state-of-the-art Bayesian framework that models the color-magnitude diagram of an observed OC as a mixture of single stars, photometric unresolved binaries, and field stars. Its advanced statistics and comprehensive physical models enable the determination of all the OC properties simultaneously with unprecedented precision and permit exciting discoveries. This method enables us to build a comprehensive OC parameter catalog, in particular, including the MF and binary properties, which were unfeasible in conventional methods. Applying the method to Gaia data, we find clear evidence of dynamical evolution in OCs for the first time. Taking NGC3532 as the first example, we find that stars with smaller mass or in the inner region tend to have less low mass-ratio binaries. Using a larger OC sample, we unveil that the MF slope evolves with cluster age: older OC has flatter MF (i.e., less low mass stars). This is because the dynamic encounters can destroy the low mass-ratio binaries (especially in the cluster center) and kick out low-mass stars. Finally, this method has a great potential to incorporate other stellar models or physical processes in OCs, such as stellar rotation or blue stragglers.

Flowing at Birth: A Dynamical Investigation of the Young Pisces-Eridanus Stream

Hanna Parul[1], Keith Hawkins[2]

[1]University of Alabama, Tuscaloosa, AL, [2]University of Texas, Austin, Austin, TX

A recent analysis of the kinematic data in Gaia has led to the discovery of multiple stellar streams in the Galactic disk. These comoving and young groups of stars can span several hundred parsecs in length and only tens of parsecs in width. Their chemical homogeneity and young age implies that stars residing in the stream might have a common origin. The lack of a central overdensity (core) along with their shape and age imply filamentary structure could be primordial. To investigate whether these young stellar stream could be a tidally stripped open cluster or primordial in nature, we run a set of dynamical N-body simulations of open clusters, modeled as King spheres with a wide range of initial masses and radii, in the Galactic potential and compared them against such stream, the Pisces-Eridanus (Psc-Eri). We show that

the spatial distribution of stars in the Psc-Eri stream could not be fitted by a dynamically evolved open cluster, which argues in favor of its primordial filamentary structure.

Effects of radially anisotropic velocity distribution on the dynamics of star clusters

Vaclav Pavlik[1], Enrico Vesperini[1]
[1]Astronomy Department, Indiana University Bloomington, Bloomington, IN

We are exploring various aspects of the dynamics of star clusters characterized by a radially anisotropic velocity distribution (see Pavlik & Vesperini 2021, 2022). In our first study, we used N-body simulations to show that radially anisotropic systems are characterized by more rapid evolution towards energy equipartition than isotropic ones. In the subsequent extension, we explored the development of mass segregation, the evolution of primordial binaries and the influence of the Galactic tidal field. I will present an overview of our results showing that in the systems with initial radial velocity anisotropy: 1) mass segregation is slower in the inner regions and more rapid in the outer regions, 2) the rate of disruption of primordial binaries is higher, and 3) the rate of binary exchange events is enhanced compared to the isotropic systems and may lead to an increased dynamical formation of binaries including a stellar remnant component.

Session: Dynamics Beyond the Main Sequence

The comet bombardment rate of solitary white dwarfs

Christopher O'Connor[1], Dong Lai[1]
[1]Cornell University, Ithaca, NY

We have studied the dynamical evolution of a comet reservoir located at distances between ~10^3 and ~10^5 AU (an "Oort cloud") during the late stages of stellar evolution, specifically the asymptotic giant branch (AGB) and white dwarf (WD) stages. Using N-body simulations, we examine how weakly anisotropic stellar mass loss during the AGB stage affects the fraction of Oort cloud comets that remain on bound orbits and the distribution function of surviving comets. We find that a small, but significant, fraction of comets remains bound to the newborn WD across a realistic range of kick velocities and mass-loss timescales. During the WD stage, we analytically estimate the rate at which the Galactic tidal field causes surviving Oort cloud comets to bombard the central star, leading to atmospheric metal pollution. We also use N-body simulations to investigate to what extent surviving planets orbiting the WD act as a barrier to comet bombardment. Based on our results, we suggest that the low observed prevalence of debris with a comet-like composition among polluted WDs indicates a significant population of unseen surviving planets acting as barriers to incoming Oort cloud comets. This is consistent with the inference of surviving planets in the ~10-100 AU range based on the observed accretion of debris from tidally disrupted rocky asteroids.

Binary asteroid scattering around white dwarfs

Catriona McDonald[1], Dimitri Veras[1]
[1]University of Warwick, Coventry

Observations of metallic pollution in white dwarf atmospheres can only be explained by the recent accretion of rocky material broadly similar in composition to rocky bodies in the Solar System. Further recent observations of transiting planetesimals around white dwarfs in a state of active disruption elicits questions about the processes and post-main-sequence planetary system architectures which can lead to asteroids being perturbed onto close-in orbits and subsequently accreted. In the Solar System, the outer planetesimal populations which are most likely to survive the intense giant branch phases of stellar evolution exhibit a high binarity fraction, with a significant population of near equal sized binary components. Here we present a previously unexplored area of post-main-sequence planetary system science which could contribute to the production of white dwarf debris systems, the dynamical evolution of binary asteroids around white dwarfs.

Through Rebound N-body integrations of equal mass binary asteroid systems in different planetary system architectures, we follow the dynamical evolution of binaries for 1Gyr of a white dwarf's lifetime. We highlight how the distribution of planetesimals within a system changes due to the effect of binary dissociation through interactions with giant and terrestrial sized planets. Further, the implications for the white dwarf pollution process due to asteroid binarity is discussed with both dissociated and gravitationally bound binary systems approaching the white dwarf with small pericenters which could be further perturbed and lead to accretion.

Probing planetary architecture evolution with post-main sequence planets

Samuel Grunblatt[1], Nicholas Saunders[2], Daniel Huber[3], Soichiro Hattori[4], Ruth Angus[1], Dimitri Veras[5], Katelyn Breivik[6], CPS Collaboration[7], TESS collaboration[8]
[1]AMNH/Flatiron CCA, New York, NY, [2]Institute of Astronomy, University of Hawai‘i at Manoa, Honolulu, HI,
[3]Institute for Astronomy, University of Hawaii, Honolulu, HI, [4]Columbia University, New York, NY,
[5]University of Warwick, BIRMINGHAM, [6]Flatiron Institute, Brooklyn, NY, [7]Caltech, Pasadena, CA,
[8]NASA/MIT, Greenbelt/Boston, MD

The evolution and stability of planetary system architectures, key to planetary habitability, remains poorly understood. Both interactions between neighboring planets as well as between the planets and their host star can sculpt planetary systems on long (> Gyr) timescales. Characterizing the planet population of post-main sequence stars can reveal the relative strength and frequency of these interactions, playing a crucial role in helping us to understand the past, present and future of planetary systems. Here we introduce the planets discovered so far as part of the TESS Giants Transiting Giants program. With star and planet mass and radius constraints, we constrain the rate and efficiency of star-planet and planet-planet interactions in these systems. We find that planets transiting evolved stars display a wide range of inflation rates, and appear to follow a generally monotonic period-eccentricity relation, where longer-period planets appear to have higher eccentricities. We compare this population to the long-period, non-transiting population of evolved planetary systems and binary stars, and demonstrate how future observations of evolved systems can bridge gaps in our understanding of the evolution and longevity of planetary systems.

Session: Planetary Transactions of Angular Momentum

Producing Moderate Stellar Obliquity through Planet Formation in Broken, Misaligned Protoplanetary Disks

Juliette Becker[1], Konstantin Batygin[2]
[1]Caltech, Pasadena, CA, [2]California Institute of Technology, Pasadena, CA

Recent observational evidence has suggested that planet-forming disks exhibit a wider range of dynamical states than has generally been considered under standard planet formation hypotheses. Simultaneously, observations of stellar obliquities with respect to nearby, transiting exoplanets show that mature systems populate a wide range in parameter space. We investigate the dynamical modes that can be attained by planets that form in broken protoplanetary disks, and how this mechanism fits into the distribution of measured stellar obliquities. Using a Hamiltonian framework, we describe how the initial disk geometry and disk dispersal will affect the final stellar obliquity with respect to exoplanets forming in the inner disk. Inspired by the recent observational census of disks, we consider planet-forming disks that include at least one gap and some difference in the direction of orbital angular momenta between the disk components. We find that for a subset of systems around cool stars, an initially broken, misaligned disk can produce a moderate (5-30 degrees) range of stellar obliquities.

Origins of Hot and Warm Jupiters from the Stellar Obliquity Distribution

Malena Rice[1]
[1]Yale University, New Haven, CT

The obliquity of a star, or the angle between its spin axis and the orbit normal of its companion planets, provides a unique constraint on that system's evolutionary history. In contrast with the solar system, where the Sun's equator is nearly aligned with its companion planets, many hot Jupiter systems have been discovered with large stellar obliquities, hosting planets on polar or retrograde orbits. I will demonstrate that the observed stellar obliquity distribution, combined with tidal dissipation from star-planet interactions, points towards high-eccentricity migration as the primary hot Jupiter formation mechanism. I will also present and contextualize the first results from the Stellar Obliquities in Long-period Exoplanet Systems (SOLES) survey, which is extending the sample of stellar obliquity measurements to include systems with wide-orbiting planets that are more representative of the primordial obliquity distribution.

A Dynamical Systems Theory Approach to Circumbinary Orbital Dynamics

Andrew Langford[1], Lauren Weiss[1]
[1]University of Notre Dame, Notre Dame, IN

Unlike The Solar System, ~20% of stars are found to be gravitationally bound, forming a binary system. A fraction of these stars, composing millions of solar systems across the galaxy, are formed in close binaries, < 1AU. To date, astronomers have confirmed ~20 circumbinary ‘P-type’ planets using transit and imaging methods, thanks largely to data from the NASA Kepler and TESS missions. Planets forming and persisting in these systems are subject to gravitational interactions with two major bodies, forming a three-body dynamics problem. Unlike its two-body counterpart, this dynamical system does not permit analytic solutions and possesses extreme sensitivities to initial conditions.

In this investigation, we have turned to applications of dynamical systems theory inspired by modern advances in multi-body astrodynamics to classify families of orbits and their stability in the Circular Restricted Three-Body Problem (CR3BP). Studying the CR3BP as a nonlinear Hamiltonian dynamical system, we have identified retrograde and prograde families of periodic solutions (limit cycles) using differential corrections algorithms. Via Floquet Theory, we can directly interpret the periodic solution's linear stability by calculating the Poincaré exponents encoded in eigenvalues of the monodromy matrix. Through this technique, we also record the locations of bifurcations associated with the termination and generation of new periodic families. To complement the study of periodic solutions, we have investigated the evolution of the global circumbinary solution space through Poincaré mapping techniques.

Mutual Inclination of Ultra-Short-Period Planets with Time Varying Stellar J2-moment

Chen Chen[1], Gongjie Li[1], Cristobal Petrovich[2]

[1]Georgia Institute of Technology, Atlanta, GA, [2]Pontificia Universidad Catolica de Chile, Santiago

Systems with ultra-short-period planets (USPs) tend to possess larger mutual inclinations compared to those with planets located farther from their host stars. This could be explained due to precession caused by stellar oblateness at early times when the host star was rapidly spinning. However, stellar oblateness reduces over time due to the decrease in the stellar rotation rate, and this may further shape the planetary mutual inclinations. In this work, we investigate in detail how the final mutual inclination varies under the effect of a decreasing J2. We find that different initial parameters (e.g., the magnitude of J2 and planetary inclinations) will contribute to different final mutual inclinations, providing a constraint on the formation mechanisms of USPs.

In general, mutual inclination decreases over time due to the decay in the J2 moment. If the inner planets start in the same plane as the stellar equator or if the planets start co-planar while misaligned with the stellar spin-axis, since the inner orbit typically possesses less orbital angular momentum. However, if the outer planet is initially aligned with the stellar spin while the inner one is misaligned, the mutual inclination nearly stays the same. Overall, our results suggest that either the USP planets formed early and acquired significant inclinations (e.g., > 30 deg with its companion or > 10 deg with its host star spin-axis for Kepler-653c) or they formed late (> Gyr) when their host stars rotate slower

Formation History of HD106906 and the Vertical Warping of Debris Disks by an External Inclined Planetary Companion

Nathaniel Moore[1], Gongjie Li[1], Lee Hassenzahl[1], Erika Nesvold[2], Fred Adams[3], Smadar Naoz[4]

[1]Georgia Institute of Technology, Atlanta, GA, [2]Giant Army, LLC, Severn, MD, [3]University of Michigan, Ann Arbor, Ann Arbor, MI, [4]University of California, Los Angeles, Los Angeles, CA

HD106906 is a planetary system that hosts a wide-orbit planet, as well as an eccentric and flat debris disk, which hold important constraints on its formation and subsequent evolution. The recent observations of the planet constrain its orbit to be eccentric and inclined relative to the plane of the debris disk. Here, we show that, in the presence of the inclined planet, the debris disk quickly (<2 Myr) becomes warped and puffy. This suggests that the current configuration of the system is relatively recent. We explore the possibility that a recent close encounter with a free floating planet could produce a planet with orbital parameters that agree with observations of HD106906b. We find that this scenario is able to preserve the structure of the debris disk while producing a planet in agreement with observation.

The impact of stellar clustering on the observed multiplicity of super-Earth systems: outside-in cascade of orbital misalignments initiated by stellar flybys

Laetitia Rodet[1], Dong Lai[1]
[1]Cornell University, Ithaca, NY

Recent studies suggest that the observed multiplicity of super-Earth (SE) systems is correlated with stellar overdensities. This correlation is puzzling as stellar clustering is expected to influence mostly the outer part of planetary systems. In this talk, I will present the possibility that stellar flybys indirectly excite the mutual inclinations of initially coplanar SEs, breaking their co-transiting geometry. We propose that flybys excite the inclinations of exterior substellar companions, which then propagate the perturbation to the inner SEs. We estimated semi-analytically the expected number of 'effective' flybys per planetary system, which can be rescaled easily for various system parameters. For a given SE system, there exists an optimal companion architecture that leads to the maximum number of effective flybys; this results from the trade-off between the flyby cross-section and the companion's impact on the inner system. We expect this mechanism to be efficient in ‘SE + two companions' systems that were born in dense stellar clusters.

Raining Rocks: Collision, capture and ejection rates of comets in planetary systems

Santiago Torres[1]
[1]University of California, Los Angeles, Los Angeles, CA

Impacts and ejections of comets and asteroids as a result of planet interaction play essential roles in forming planetary systems. They, for example, lead to the formation of Kuiper belts and Oort cloud-like structures, create interstellar comets, and can drastically change the development of life. In particular, the impacts of comets or asteroids onto planets can lead to complete atmospheric loss, jeopardizing the planet's future evolution. We will present a novel analytic formulation for calculating the rates at which minor bodies collide, get captured, and are ejected into interstellar space due to the interaction with planets. By computing and comparing to a suite of detailed N-body simulations, we confirmed the accuracy of our analytic formulation. We first calculate the collision rates for the planetary systems detected by Kepler and TESS. To do this, we distributed minor bodies in Kuiper belt/Oort cloud-like structures adapted for each planetary system architecture. The resulting collision rates extend from 1e-9 up to 1e-2 comet/year. Hot-Jupiters experience the highest collision rates, which compromises the stability of their atmospheres. Second, we will present new estimations for capture rates of minor bodies by planets and the ejection rates into interstellar space. With our simple analytical formulation, we can predict planetary atmospheric loss, the formation of a family of comets orbiting planets, and the interstellar comet production rate for different planetary architectures. These predictions will guide future observational surveys to search for planets with stable atmospheres, cometary structures around planets, and objects in the interstellar space.

Session: Tides

Tidal Dissipation in the Saturnian System

Robert Jacobson[1]
[1]Jet Propulsion Laboratory, La Crescenta, CA

In our development of the Saturnian satellite ephemerides to support the

Cassini tour of the Saturnian system we did not take into account tidal forces. However, Lainey et al. (2012 Astrophys. J. **752**, 14), Polycarpe et al. (2018 A&A **619,** A133), and Lainey et al. (2020 Nature Astron. **4,** 1053) have published investigations of tidal effects in the Saturnian system. Consequently, for our post-*Cassini* ephemeris work in preparation for the future *Dragonfly* mission to Titan we decided to include the effects of tides raised on the planet by the six innermost major satellites (Hyperion and Iapetus are too distant to be strongly influenced by tides). We also included the tide raised on Enceladus by Saturn because its effects are of interest in the thermal and orbital evolution of that satellite (Nimmo et al., 2018 in Enceladus and the Icy Moons of Saturn, Schenk et al. Eds., Univ. Arizona Press). In this paper we describe our model for the tidal forces and report the values of the tidal quality factors, *Q,* determined in the course of our ephemeris development. Because planets and satellites are not perfectly elastic, the friction within them produces a time delay in the raising of a tidal bulge on them and causes energy dissipation within them. The quality factor is a measure of that dissipation. We compare our tidally accelerated satellite orbits with those used for the final reconstruction of the *Cassini* tour. We find that five of the six satellites are spiraling out from Saturn as a consequence of the acceleration caused by the tidal bulge raised on Saturn. But Enceladus is spiraling inward as the tide raised on it by Saturn overwhelms the tide raised by it on Saturn.

Dynamical Tidal Love Numbers of Rapidly Rotating Planets and Stars

Janosz Dewberry[1], Dong Lai[2]
[1]Caltech, Pasadena, CA, [2]Cornell University, Ithaca, NY

Tidal interactions play an important role in many astrophysical systems, but uncertainties regarding the tides of rapidly rotating stars and gaseous planets remain. In this presentation, I will describe recent research focused on the dynamical tidal response of rotating, centrifugally distorted planets and stars. We compute the frequency-dependent Love numbers of polytropes with indices appropriate for gas giants and some neutron stars, and rotation rates up to ~90% of "break-up." Through a representative application to Jupiter, we evaluate the potential relevance of inertial wave resonances with the planet's satellite moons, and also provide an analytical explanation for anomalously large values of "tesseral" Love numbers measured by the satellite Juno. At rapid rotation rates close to break-up, we find strong mode mixing associated with "avoided crossings," and explore the interplay between tidal resonance and the secular Chandrasekhar-Friedman-Schutz instability. We additionally tabulate polynomial fits to relevant normal mode properties, providing a much simpler method of computing the tidal response across a wide range of rotation rates.

Session: Binary Stars

The Astrometric Contribution of Unresolved Stellar Companions in Gaia

Zephyr Penoyre[1], Vasily Belokurov[1], Wyn Evans[1]

[1]University of Cambridge, Cambridge

The most ubiquitous oddity of stars is that they are not a single object, but a binary (or higher multiple) - indistinguishable in many ways but with a whole panoply of new dynamical behaviours and paths for evolution.

Precise astrometry can resolve the slight excess motion caused by a companion, and the thousand-fold increase in precision afforded by the Gaia survey can be expected to yield a similar thousand-fold increase in detectable astrometric binaries.

Fitting a single-star model is easy, so much so that we do it to every source by default. An unresolved binary companion will perturb this fit, biasing the inferred position, motion and parallax, and introducing extra error irreconcilable with the single-star model. Thus we can detect, constrain and start to classify a huge number of astrometric binary systems, with periods from ~ a month to a decade, from the already available Gaia data, its error, and the small shifts between data releases.

In this talk I'll introduce in more detail the character of the astrometric contribution of binary systems, and thus how the observability depends on the properties of the system. I will also introduce simple methods for selecting relatively reliably binary candidates and present the properties of such nearby candidates in Gaia eDR3.

Eccentricity of wide binary stars

Hsiang-Chih Hwang[1], Yuan-Sen Ting[2], Nadia Zakamska[3]
[1]Institute for Advanced Study, Princeton, NJ, [2]Australian National University, Canberra, [3]Johns Hopkins University, Baltimore, MD

Eccentricity is one of the fundamental orbital parameters in orbital dynamics. It not only provides critical constraints on binary formation mechanisms, but also plays a key role in the formation of hot Jupiters and close binaries via the secular three-body interaction. However, eccentricity is challenging to measure for wide binaries due to their extremely long orbital periods. In this talk, I will show that we can infer the eccentricity distribution of wide binaries even when we only have a snapshot of their orbits. In particular, with Gaia data, we use the “v-r angle”, the angle between the separation vector and the relative velocity vector in a wide binary, to infer binary eccentricities. I will present that the eccentricity distribution strongly depends on binary separations, and it becomes a mysterious super-thermal distribution at > 1000 AU. I will further discuss how eccentricities change among subsamples of wide binaries, especially equal-mass wide binaries. This v-r angle method provides a new technique for measuring eccentricities for long-period systems, critical for understanding binary formation, evolution, and stellar orbits in the Galactic center and globular clusters.

The eccentricity distribution of wide binaries in the Galaxy

Chris Hamilton[1]
[1]Institute for Advanced Study, Princeton, NJ

GAIA has allowed astronomers to probe for the first time the phase space distribution function (DF) of the Keplerian orbital elements of wide binaries in the Solar neighbourhood. This DF exhibits non-trivial features, in particular an unexplained superthermal distribution of eccentricities for binaries with semimajor axes > 1000 AU. To interpret such features we must first understand how the binary DF is affected by dynamical perturbations, which typically fall into two classes: (i) stochastic kicks from passing stars, molecular clouds, etc. and (ii) secular torques from the Galactic disk. In this talk I will isolate effect (ii) and show how one can compute the time-asymptotic, phase-mixed DF for an ensemble of wide binaries under the Galactic tide. I will discuss what the resulting eccentricity and inclination distributions can tell us about the formation mechanisms of wide binaries in the Milky Way.

Session: Advances in Theory and Numerics for Galactic Dynamics

Observing Fundamental Dynamics in the Milky Way: Stream Morphologies, Separatrices, and Dark Matter Potentials

Tomer Yavetz[1], Kathryn Johnston[1,2]
[1]Columbia University, New York, NY, [2]Center for Computational Astrophysics, Flatiron Institute, New York, NY

Stellar streams, formed from the tidal disruption of globular clusters and dwarf galaxies, have long been used as dynamical tracers to help characterize the Milky Way's gravitational potential and its dark matter halo. Recent observations have revealed that some streams, such as Jhelum, Atlas Aliqa Uma (AAU), and Palca, exhibit more complex morphologies, including fans, bifurcations, and multiple separate components. I will explain how such features can arise from transitions, or separatrices, between the orbit families supported by non-spherical potentials. In the particular case of the three aforementioned streams, I will show simulations of objects on similar orbits exhibiting morphological features that result from this dynamical mechanism, and that are reminiscent of the observed systems. I will discuss how these findings may be used to help determine the precise shape of the gravitational potential of the Milky Way's halo.

Dynamical Friction, Core Stalling & Dynamical Buoyancy

Frank Van Den Bosch[1], Uddipan Banik[1]
[1]Yale University, New Haven, CT

Numerical simulations have shown that dynamical friction dissapears inside constant density cores, and that massive objects inside a core can even experience a dynamical buoyancy that `pushes' them outwards. Such phenomena may have important implications for the merger-rate of black holes in the centers of dwarf spheroidals, or for the ability of nuclear star clusters to form via the merging of globular clusters.

Core stalling is not captured by the standard Chandrasekhar treatment of dynamical friction, and even the resonance-picture based on the Lynden-Bell Kalnajs (LBK) torque fails to explain dynamical buoyancy. In this talk I will present two new approaches towards an improved understanding of dynamical friction at large, and of core stalling in particular. After highlighting the shortcomings of the standard formalism based on the LBK torque, I present a more general, self-consistent treatment and demonstrate that it reproduces all aspects of core stalling observed in N-body simulations. Next I present a novel non-perturbative, orbit-based approach that gives valuable insight as to the workings of dynamical friction and dynamical buoyancy. Due to a bifurcation of Lagrange points that occurs when a perturber approaches a core, the near co-rotation resonance orbits that are responsible for friction change their character, which ultimately explains why the direction of the torque acting on a perturber changes sign as it approaches the core region.

A new instability in dark-matter halos

Martin Weinberg[1]
[1]University of Massachusetts, Amherst, Amherst, MA

Isotropic dark-matter (DM) halos have weakly damped point modes. The l=1 mode is a seiche mode and the l=2 is the precursor to the radial-orbit instability (ROI). I will show that small deviations in the distribution function (DF) can destabilize these modes and leads to a newly identified instability for NFW-like DM halos. These modes have been corroborated using linear-response theory and identified in simulations using singular spectrum analysis. The non-linear development of the new mode correlates the radial angle of eccentric orbits and leads to a density enhancement that swings from one side of the halo to another along a diameter. This mode is the l=1 analog of the ROI. The density amplitude reaches 10% at saturation in n-body simulations. The l=1 growth rate increases with increasing extent and the amplitude of excursions in the outer distribution. Since the DF is unlikely to be smooth, these modes may be ubiquitous in physical systems. Halos that are less extended than NFW, such as the Hernquist model, do not have unstable l=1 but are susceptible to unstable l=2. For outer slopes with exponents between Hernquist and NFW: both instabilities can coexist. These instabilities illustrate a more general property of DM halos: the overall DM response depends sensitively on the outer density profile. In particular, the halo response to satellites will depend on the outer halo profile as well as the inner profile.

Coupling Basis Function Expansion with Multi-Channel Singular Spectrum Analysis: a Powerful Toolkit for Dynamical Systems.

Alexander Johnson[1], Michael Petersen[2], Kathryn Johnston[1], Martin Weinberg[3]
[1]Columbia University, New York, NY, [2]Institut d'Astrophysique de Paris, Paris, [3]University of Massachusetts, Amherst, Amherst, MA

Dynamical evolution of astronomical systems is driven by a complex interplay of features on many scales, both in simulations and in nature. Until now, there have been few tools that enable discovery of the underlying dynamical processes. We develop the combination of basis function expansions (BFEs) with multi-channel singular spectrum analysis (M-SSA) to address this challenge for the case of self-gravitating systems described by phase-space distribution functions. When applied to a simulation of an isolated Milky-Way-like galaxy the BFE/M-SSA combination is able to cleanly separate three low level features in this near-equilibrium, multi-component system: particle noise; phase-mixing from an initially mild disequilibrium; and structures forming due to a dynamical coupling of the disk and halo components. These successes demonstrate the power of this technique as a toolkit for dynamical analysis more generally.

Collisionless gravitational systems: discrete or not discrete? - that's the question

Leandro Beraldo e Silva[1]
[1]University of Michigan, Ann Arbor, MI

A collisionless gravitational system, starting from a generic configuration, evolves towards a stationary state. In the limit N -> infinity (continuum limit), this is accompanied by the development of indefinitely fine structures in phase-space. This continuum hypothesis is traditionally assumed to break only on time scales compared to the two-body relaxation time (~ 0.1 * N / ln N). In this talk, I will show the existence of a much shorter relaxation time scale [~ 0.1 * N^(1/6)], after which phase-space gets degraded, and finer structures are precluded. For stars in a galaxy [N~10^(11)], this happens in a few dynamical times,

solving the old problem of the fast relaxation of collisionless systems without the subjective effect of coarse-graining. On the other hand, this may restrict the capability of N-body simulations to reproduce fine structures expected for dark matter halos.

Special Session: Modern Theories of Planetesimal Formation

Thresholds for Planetesimal Formation by the Streaming Instability

Rixin Li[1], Andrew Youdin[2]
[1]Cornell University, Ithaca, NY, [2]University of Arizona/Stewart Observatory, Tucson, AZ

The crucial first step in planet formation is to build planetesimals out of dust particles in gaseous protoplanetary disks. The Streaming Instability (SI) is one of the leading mechanisms to concentrate solids in disks and rapidly produce planetesimals. In this talk, I will present our latest work on quantifying the physical conditions needed by the SI to form planetesimals. Specifically, we focus on two parameters that control the SI behaviors: particle size and metallicity (i.e., solid abundance relative to the gas). Our high-resolution simulation results pinpoint a metallicity threshold as a function of particle size. We find that planetesimal formation can occur even at sub-solar metallicities, consistent with recent disk observations that suggest planet formation is well underway at early evolutionary stages. I will also show how our results can be applied to general turbulent disk models. Finally, I will present our preliminary results on the thresholds for planetesimal formation in self-gravitating disks and discuss the implications on early planet formation.

The Streaming Instability with Multiple Dust Species in Protoplanetary Disks

Chao-Chin Yang[1], Zhaohuan Zhu[1]
[1]University of Nevada, Las Vegas, Las Vegas, NV

The streaming instability is a fundamental process that can drive dust-gas dynamics and ultimately planetesimal formation in protoplanetary disks. However, it has recently been shown that the instability with a distribution of dust sizes may not operate efficiently under certain conditions, hence a revisit to the instability becomes necessary.

Using linear analysis, we systematically explore an unprecedentedly large parameter space spanned by the limits and slope of the dust-size distribution and the total dust-to-gas density ratio. We show that the growth of the instability can be classified into two distinct regimes—fast- and slow-growth—, depending mainly on the leading dust size $\tau_{s,max}$ and the total dust-to-gas density ratio ε. The regime of fast growth requires either large $\tau_{s,max}$ or large ε, and the two regimes are distinctly separated by a sharp boundary in the $\tau_{s,max}$–ε space, while this boundary is not appreciably sensitive to the slope or the lower end of the dust-size distribution. We further conduct numerical simulations of an unstratified disk into nonlinear saturation of the instability. For the fast-growth regime, the one system with small $\tau_{s,max}$ but large ε drives turbulent vertical dust-gas vortices, while the other with large $\tau_{s,max}$ leads to radial traffic jams and filamentary concentrations of dust particles. By contrast, a system in the slow-growth regime results in a virtually quiescent state.

Although the saturation states in the fast-growth regime are similar to their single-species counterparts, a wealth of information can be found with the multi-species streaming instability. We find that the dust density distribution driven by turbulent vortices is flat in low densities, while the one undergoing traffic jams has a low-end cutoff. Moreover, we find that in the fast-growth regime, significant dust segregation by size occurs, with large particles moving towards dense regions while small particles remain in the diffuse regions, and the mean radial drift of each dust species is appreciably altered from the (initial) drag-force equilibrium. The former effect may skew the spectral index derived from multi-wavelength observations and change the initial size distribution of a pebble cloud for planetesimal formation. The latter effect along with turbulent diffusion may influence the radial transport and mixing of solid materials in young protoplanetary disks.

The Formation of Planetesimals by the Streaming Instability

Jacob Simon[1], David Nesvorny[2], Rixin Li[3], Andrew Youdin[4], Daniel Carrera[1], Philip Armitage[5]
[1]Iowa State University, Ames, IA, [2]Southwest Research Institute, Boulder, CO, [3]Cornell University, Ithaca, NY, [4]University of Arizona/Stewart Observatory, Tucson, AZ, [5]Stony Brook University, Stony Brook, NY

One of the largest unanswered questions in planetary astrophysics is: how do planetesimals form? In this talk, I will briefly review one of the leading candidates for planetesimal formation: the streaming instability. I will then describe recent progress made in studying this mechanism via high-resolution, state-of-the-art numerical simulations. These simulations have led to a number of predictions that are being tested with observations of Solar System planetesimal populations. I will describe the results of these tests and then outline future directions to further understand this instability and what it implies for the formation of planetesimals.

Pebble Cloud Collapse, a Revolution in Planetesimal Formation

Wesley Fraser[1]
[1]Herzberg Institute of Astrophysics, Victoria, BC

In the last two decades, we have experienced a significant shift in our thoughts about the early stages of planet formation, and in particular, the growth from dust and pebbles into ~100 km-scale planetesimals. The idea that gas-pebble interactions could drive super concentrations of solid material so as to collapse under self-gravity and thereby form large-scale bodies has indeed proven revolutionary. The outcomes of numerical simulations of formation via *pebble cloud collapse* do quite well in matching the observed properties of the telescopically accessible planetesimal populations that have yet to be matched in the various flavours of the more classical accretion mode of hierarchical growth. Critically, via virtue of the short ~100 yr collapse timescales that these clouds experience, formation via this route naturally avoids the scourge of hierarchical growth models: the metre-barrier. I argue that the evidence for this new formation route is overwhelming. In this talk I try to convince the audience of this, by highlighting some of the key observables of the asteroids and Kuiper Belt Objects that support pebble cloud collapse, including binarity of the bodies and the properties of those binary systems, and their size distributions. I will discuss how those observables constrain numerical models, and indeed, reject numerous others. In particular, I will highlight what aspects of cloud collapse models remain largely unconstrained, and point out experiments, both numerical and observable, that can improve those constraints. I will finish with a discussion of the contact binary Kuiper Belt Object Arrokoth, which is now held up as a glaring nail in the coffin of hierarchical accretion, at least for the outer Solar System's denizens. While I agree with this sentiment, I will discuss the possibility that Arrokoth may not be a direct product – the central body – of cloud collapse. Rather, I suggest that Arrokoth is simply the detritus ejected during the collapse of a cloud, thereby avoiding accretion into a larger body.

Interstellar planetesimals as diagnostics of galactic star-formation history

Michele Bannister[1], Chris Lintott[2], J. Ted Mackereth[3]
[1]University of Canterbury, Christchurch, [2]University of Oxford, OXFORD, [3]CITA/Dunlap Institute/
University of Toronto, Toronto

The population of interstellar objects are diagnostic both of the formation conditions of their planetary disks, and of the metallicity of the stellar environment in which they were born. When planetesimals are dispersed from their system of origin, this record is carried with them. As objects that then travel through the Solar System, they offer the prospect of placing experimental constraints on Galactic history — with a very different lens to that of Galactic archaeology. Using the EAGLE cosmological simulations and models of protoplanetary formation, our modelling predicts an ISO population with a bimodal distribution in their water mass fraction: objects formed in low-metallicity, typically older, systems have a higher water fraction than their counterparts formed in high-metallicity protoplanetary disks, and these water-rich objects comprise the majority of the population. The population of ISOs in galaxies with different star formation histories will have different proportions of objects with high and low water fractions.

The Role of Particle Contact Physics in Planetesimal Formation

Jackson Barnes[1], Stephen Schwartz[2], Seth Jacobson[1]
[1]Michigan State University, East Lansing, MI, [2]University of Arizona, Tucson, AZ

Growth barriers limit the pairwise growth of pebbles in the protoplanetary disk to cm sizes, hindering planetesimal formation. Growth up to 100-km planetesimal sizes may occur beyond these barriers via the gravitational collapse of clouds of pebbles gathered by interactions with nebular gas, i.e. the streaming instability (Youdin & Goodman 2005; Johansen et al. 2007; Carrera et al. 2021a). The abundance of Kuiper belt binaries is evidence of this process, as excess angular momentum leftover from the SI would prevent the coalescence of a pebble cloud into a single body (Nesvorný et al. 2010, 2019, 2021; Robinson et al. 2020). Yet, the role of contact physics between colliding pebbles during gravitational collapse has not been explored. In this work, we have examined the effects of varying these parameters on the formation of planetesimal systems, particularly in regard to individual planetesimal morphology and rotation states, system dynamics, and planetesimals' collisional histories.

We modeled gravitational collapse using the PKDGRAV N-body integrator (Richardson et al. 2000; Stadel 2001) and its soft-sphere discrete element method, which ensures that colliding particles stick and rest upon one another rather than merging to form a single larger spherical particle (Schwartz et al. 2012). Because we do not use an inflation factor to enhance the collision rate, our particles maintain realistic densities. The use of inflation factors may also induce overly vigorous planetesimal growth, prevent the formation of tightly orbiting systems, and bias final systems towards binarity rather than higher number multiplicity. Moreover, one cannot accurately determine planetesimal shapes and spins in perfect-merging models. The SSDEM's ability to monitor contact forces between particles is necessary to form a complete theory of planetesimal formation.

All of our simulations successfully create binary systems, each containing a single large primary and bound secondary planetesimal as well as many smaller binary systems. Gravitational collapse is very efficient. With the inclusion of varied particle frictional forces and coefficients of restitution we see the formation of planetesimal systems with a wide array of dynamics. Our largest systems exhibit mild dynamics with mutual orbital distances ranging from 10^2-10^3 km. Smaller systems exhibit a wide range of inclinations, high eccentricities, and tight orbits of <100 km with some coming into near contact. As this is a low-resolution preliminary study, we aim to investigate the effects of particle contact physics on the collapse of high-resolution clouds soon.

The dynamical role of drag force in gravitational instability: a path to form planetary cores in young protostellar discs

Cristiano Longarini[1,2], Giuseppe Lodato[1], Giuseppe Bertin[1], Philip Armitage[2,3]
[1]Università degli Studi di Milano, Milan, [2]Stony Brook University, Stony Brook, NY, [3]Flatiron CCA, New York, NY

Explaining the formation of planetesimals is challenging for current planet formation scenarios. Indeed, according to Core Accretion theory, the timescale of solid cores formation is up to 1Myr, too long to explain the plethora of protoplanets observed in class II protostellar discs. As for the Gravitational Instability scenario, the expected mass of fragments is about 1 to 10 Jupiter masses, too big to form a planetary core.

In addition, the wide diversity of substructures such as rings, gaps, spirals in ALMA protoplanetary systems is often explained by the interaction between massive embedded protoplanets and the accretion disc. This necessarily implies that planet formation is already underway in young systems, when the protostar is still embedded into the molecular cloud and the accretion disc is massive. In these environments, the role of self gravity and gravitational instability is decisive in determining the dynamical evolution of the system. For this reason, studying the role of dust in gravitational instability is crucial to obtain a comprehensive knowledge of planetesimal formation process.

In this work, we present an analytical framework to study gravitational instability of a gas and dust disc, including the effect of drag force, as a path to solve the conundrum of planetesimal formation in protoplanetary discs. We found that the instability is determined by three parameters, that are the dust to gas ratio, the relative temperature between the two components and the Stokes number, that measures the strength of the aerodynamical coupling. When we consider the dynamical and gravitational effect of dust, the instability threshold is always higher compared to the one fluid model. In addition, the presence of the second component can trigger gravitational instability at very short wavelengths, reducing of several order of magnitudes the Jeans length and mass. In this picture, considering typical protoplanetary discs parameters, the Jeans mass can be of the order of the Earth mass, much lower compared to the one fluid scenario. In this respect, this phenomenon is a possible path to form planetary cores in early protoplanetary stages.

Suppression of collision velocities in particle-laden protoplanetary disk turbulence

Natascha Manger[1], Philip Armitage[1,2], Zhaohuan Zhu[3], Chao-Chin Yang[3]
[1]Flatiron Institute CCA, New York, NY, [2]Stony Brook University, Stony Brook, NY, [3]University of Nevada, Las Vegas, Las Vegas, NV

Understanding how the collision of dust grains is regulated by the turbulence generated in protoplanetary disks is key to understanding the growth of particles from a few nm to cm sized objects. But while particle clustering in gas-dominated turbulence is well understood, the clustering behavior in turbulence with significant dust-loading has not been investigated.

Here we perform turbulence simulations using dust to gas ratios between 10^{-2} and 10 and for a range of particle stopping times, showing that the particle collision velocities are reduced significantly when increasing the dust-to gas ratio of the simulations. Also, we find that increasing the dust-to-gas ratio changes the particle clustering at small scales, shifting the radial distribution function to mimic the behavior of particles with smaller particle stopping times. This means that significantly larger particles are able to grow through sticking collisions within regions with high particle concentration (such as zonal flows and vortices), affecting the maximum size of grains visible to (sub-)mm observations and the growth of the streaming instability in those regions.

Tuesday April 26

Session: Binary Asteroids and Radiation Forces

Non-zero Yarkovsky acceleration for near-Earth asteroid (99942) Apophis

Jorge Perez-Hernandez[1], Luis Benet[2]

[1]Telespazio Germany GmbH, Darmstadt, [2]Universidad Nacional Autonoma de Mexico, UNAM, Mexico

The leading source of uncertainty to predict the orbital motion of asteroid (99942) Apophis is a non-gravitational acceleration arising from the anisotropic thermal re-emission of absorbed solar radiation, known as the Yarkovsky effect. Previous attempts to obtain this parameter from astrometry for this object have only yielded marginally small values, without ruling out a pure gravitational interaction. Here we present an independent estimation of the Yarkovsky effect based on optical and radar astrometry which includes observations obtained during 2021 [1]. Our numerical approach exploits automatic differentiation techniques, as implemented in our own open-source software. We find a non-zero Yarkovsky parameter, $A_2 = (-2.899 \pm 0.025) \times 10^{-14}$ au d^{-2}, with induced semi-major axis drift of (-199.0 ± 1.5) m yr^{-1} for Apophis. This result is consistent with preliminary estimates [2], as well as the latest orbital solution from JPL. Our results provide definite collision probability predictions for the close approaches in 2029, 2036, and 2068. We acknowledge financial support from the PAPIIT-UNAM project IG-100819, and computer time provided through the project LANCAD-UNAM-DGTIC-284.

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Near-Critical Rotation of Binary Asteroid Primaries

Matija Cuk[1], Seth Jacobson[2], Kevin Walsh[3]
[1]SETI Institute, San Jose, CA, [2]Michigan State University, East Lansing, MI, [3]Southwest Research Institute, Boulder, CO

About 15% of km-sized asteroids are binaries, typically with a rapidly spinning primary. It is widely accepted that these pairs formed as radiation forces accelerated the primary's rotation beyond gravitational stability, It is still unknown whether the secondary forms through a catastrophic breakup or a steady mass loss, and whether the component masses and orbits of observed binaries are currently evolving or are in a stable state. It has been proposed by Jacobson and Sheeres (2011) that most observed binaries are in equilibrium between outward tidal evolution and inward BYORP radiation-driven migration. Observations (Scheirich et al. 2015, 2021) suggest that some systems may be in equilibrium while the others have evolving mutual orbits. Here we examine how the proximity of the primary's rotation to the critical limit (i.e. breakup) may affect the long-term dynamics of the binary. We find that classical tidal theory needs major revision for the case of near-breakup rotation; this applies to all gravity-dominated bodies, including km-sized asteroids thought to be ``rubble piles''. Near-critical rotation can enhance tidal effects as the effective gravity on the equator can be very weak for near-critically-rotating bodies. This ``spin-boosting'' of tides depends sensitively on the proximity to the exact rate of critical rotation, which is not always possible to determine from observations. We assess the potential strength of spin boosting in observed binaries and we find that according to the results of Pravec et al. (2016), when satellites are not in synchronous rotation, primaries are closer to the breakup spin rate. We will discuss the implication of this trend, and the possibility that mass transfer may be more important in some of these systems than long-term tidal interactions.

Modeling the Chaotic Dynamics of Binary Asteroid 1991 VH

Alex Meyer[1], Daniel Scheeres[1], Conor Benson[1]
[1]University of Colorado, Boulder, Boulder, CO

Binary asteroid 1991 VH is a target of the upcoming Janus mission, launching later this year. This system is unique in that it exists in a chaotic state and not in a synchronous spin-orbit resonance, unlike most similar near-Earth binary asteroids. Unfortunately, the shape of the secondary in this system is unconstrained. We simulate the dynamics of 1991 VH using the General Use Binary Asteroid Simulator (GUBAS) testing a variety of secondary shapes and spin states. GUBAS allows for the use of a polyhedron shape model for the primary, calculating the fourth degree and order gravity field. Given the uncertainty on the secondary's shape, we approximate it as an ellipsoid. We find that the system dynamics are strongly dependent on the shape, spin, and orientation of the secondary.

Beyond the secondary geometry and spin, we also find that out-of-plane excitation can have a significant impact on the system's dynamics. Systems that are stable in planar orbits can become chaotic when inclination or out-of-plane rotation is added to the system. This is important to consider, as chaotic systems may be less efficient at dissipating energy through tidal forces.

In preparation of the Janus flyby of 1991 VH in 2026, we simulate a variety of different systems fitting within the current system uncertainty. These simulations demonstrate the wide variety of dynamics possible in this system and shed light on the cause of its chaotic state. By comparing our results to observations of the system's mutual orbit period, we attempt to constrain the possible combinations of system geometry and dynamics and build expectations to be tested by the flyby data.

A new binary-YORP effect model combining full two rigid body dynamics and three-dimensional thermal evolution

Ryota Nakano[1], Masatoshi Hirabayashi[1]
[1]Auburn University, Auburn, AL

An extension of the YORP effect theory [e.g., 1] to a binary asteroid system is called binary-YORP (BYORP) effect, whereby the orbit of its secondary is modified on a long term due to a thermally induced torque [2]. BYORP adds additional torques and forces to the secondary, inducing its complex dynamical behavior. Within a long period, it expands/contracts the secondary's orbit, particularly by controlling the semi-major axis, *a*, and the eccentricity, *e*. Together with mutual body tides (which dissipates energy and always expands *a*), BYORP is likely to be responsible for forming a wide variety of asteroid evolution processes leading to various geophysical configurations such as, contact binaries, asteroid pairs, and ternary [3].

Here, we introduce a new BYORP model which simultaneously simulates the highly coupled mutual gravitational interaction of the non-spherical bodies, known as the full two-body problem (F2BP) [4], and the three-dimensional (3D) thermophysical condition of the secondary. This model employs Finite Element Modeling approaches [5, 6]. The BYORP-induced orbital evolution can be thus described in unprecedented detail, compared to earlier models which neglect F2BP dynamics and detailed thermal evolution. With ongoing code development, future versions of the model will further capture complex behaviors driven by mutual gravity interactions and thermal conditions (e.g., eclipse and mutual heating due to scattered sunlight).

Using the model, we investigate the BYORP-induced evolution of the binary asteroid system (61839) Didymos, the target of NASA's DART mission [7]. Based on historical observations, *a* is reported to be shrinking at -0.076 cm yr^{-1} [8].

Table 1 summarizes the physical and material properties. Dimorphos' shape is currently assumed to be a tri-axial ellipsoid. Propagating the mutual dynamics for 1 day (~2 orbital periods) on Jan 1, 2021, we find that *a* is shrinking, compared to the case where BYORP is turned off (Fig. 1). This is consistent with the observation. Importantly, however, the illumination geometry changes over the system's heliocentric orbit, and thus, it is possible that BYORP expands *a* for some epochs. In the presentation, we will present the semi-major axis evolution over the system's one heliocentric orbit.

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Predictions for the Dynamical State of the Didymos Binary System Before and After the DART Impact

Harrison Agrusa[1], Derek Richardson[1], Alex Meyer[2], Brent Barbee[3], William Bottke[4], Andrew Cheng[5], Siegfried Eggl[6], Fabio Ferrari[7], Masatoshi Hirabayashi[8], Ozgur Karatekin[9], Jay McMahon[2], Stephen Schwartz[10,11], DART Dynamics Working Group[5]
[1]University of Maryland, College Park, College Park, MD, [2]University of Colorado Boulder, Boulder, CO, [3]NASA Goddard Space Flight Center, Greenbelt, MD, [4]Southwest Research Institute, Boulder, CO, [5]Johns Hopkins, APL, Laurel, MD, [6]University of Illinois at Urbana-Champaign, Champaign, IL, [7]University of Bern, Bern, [8]Auburn University, Auburn, AL, [9]Royal Observatory of Belgium, Brussels, [10]Planetary Science Insitute, Tuscon, AZ, [11]University of Arizona, Tucson, AZ

NASA’s Double Asteroid Redirection Test (DART) is the first full-scale demonstration of a kinetic impactor for planetary defense. The spacecraft is expected to impact Dimorphos, the secondary component of the Didymos binary asteroid system, in late September of 2022. The impact will cause a reduction in the binary semimajor axis and orbital period that will be measured with ground-based observations. By measuring the change in the binary mutual orbit period, the DART mission will provide an estimate of the momentum transfer enhancement factor, β, a critical parameter that describes the additional momentum transfer generated from escaping ejecta. Launching in 2024, ESA’s Hera spacecraft will rendezvous with Didymos to further characterize the system and the effects of the DART impact. Together, these spacecraft comprise the Asteroid Impact and Deflection Assessment (AIDA) cooperation between NASA and ESA. The Didymos system is a prototypical example of the Full Two-Body Problem (F2BP), where the translational and rotational dynamics are non-Keplerian and highly coupled owing to the irregular body shapes and their close separation.

Here we present a summary of current predictions for the dynamical state of the Didymos system before and after the DART impact. First, we focus our efforts on predicting the pre-impact spin state of the secondary, whose shape and spin are unknown. Then, we investigate the secondary’s post-impact attitude evolution and show that it is highly dependent on β and its own body shape which is assumed to be a triaxial ellipsoid. We show that Dimorphos’s spin state may evolve chaotically, depending on its shape, due to various resonances between the mean motion and Dimorphos’s libration and spin precession frequencies. Finally, we discuss the future prospects for measuring Dimorphos’s post-impact spin state as well as the implications of Dimorphos’s spin state for Hera’s arrival in 2026.

Session: Cosmological footprints in Local Group dynamics

The Magellanic Stream at 20 kpc: A New Orbital History for the Magellanic Clouds

Scott Lucchini[1], Elena D'Onghia[1], Andrew Fox[2]

[1]University of Wisconsin - Madison, Madison, WI, [2]STScI, Baltimore, MD

The Large Magellanic Cloud (LMC) has had an enormous impact on the evolution and dynamics of the Milky Way (MW). Understanding the orbital history of the LMC, as well as its partner the Small Magellanic Cloud (SMC), is crucial to more precisely constrain the dynamics and evolution of the Milky Way and the Local Group. Using high resolution hydrodynamic simulations, we have recently determined a new possible orbital history for the Magellanic Clouds consistent with their present day observed proper motions that is able to recreate the Magellanic Stream, the massive gaseous structure trailing behind the Clouds. Most interestingly, the Stream formed through this new orbital history reaches as close as 20 kpc from the Sun (contrasting with previous models predicting distances of 100-200 kpc and beyond). This nearby Stream could fall onto the MW disk in as little as 50 Myrs, and with ~10^9 Msun of total gas this could drastically change the structure of our Galaxy. We could test the prediction of a 20 kpc Stream by searching for UV absorption lines towards distant MW halo stars projected onto the Stream. In this talk, I will present these new models and discuss some of the many implications of this new paradigm for the Magellanic Stream.

Implications of the travel velocity of the Milky Way on Local Group mass estimates from the Timing Argument

Katie Chamberlain[1], Adrian Price-Whelan[2], Gurtina Besla[1], Emily Cunningham[2], Nicolas Garavito-Camargo[2], Jorge Penarrubia[3], Michael Petersen[4]

[1]University of Arizona, Tucson, AZ, [2]Flatiron Institute, New York, NY, [3]University of Edinburgh, Edinburgh, [4]Institut d'Astrophysique de Paris, Paris

The total mass of the Local Group (LG) is a fundamental quantity that enables interpretation of the orbits of its constituent galaxies and is needed to place the LG in a cosmological context. However, measuring the LG mass is not straightforward, as the distribution and quantity of dark matter is unknown. One method of determining the LG mass is the Timing Argument (TA), which models the dynamics of the MW—M31 system as a two-body (Keplerian) orbit, and which depends strongly on the measured kinematics of M31. Previous TA studies of the LG mass have attempted to correct for the impact of the LMC on the inferred mass, but suffer from unknowns in the mass and dynamical modeling of the LMC interaction with the MW. However, recent studies of tracers in the MW stellar halo have found that the MW disk is moving with a lower bound “travel velocity” of 32±4 km/s with respect to its outer halo, a byproduct of its merger history and the recent pericentric passage of the LMC. This novel measurement allows us to place model-independent, empirical constraints on the LG mass that account for the measured reflex motion of the disk for the first time. In this talk, I will present our TA model that incorporates the travel velocity of the MW disk using several different compilations of recent kinematic measurements of M31. I will show that we recover lower LG masses than past TA results, and measure a total mass of $\sim 4.5 \pm 0.7 \times 10^{12}$ Msun that is consistent between datasets. Additionally, I will explain how measurements of more distant tracers may yield even larger values for the travel velocity, which would further decrease the inferred LG mass. As a result, the newly measured travel velocity directly implies a lower LG mass than from a system with a static MW halo, and must be considered in future dynamical studies of the Local Volume.

Orientations of Dark Matter Haloes in CDM and SIDM Latte Galaxies

Jay Baptista[1], Robyn Sanderson[2], Daniel Huber[3], Andrew Wetzel[4], Omid Sameie[5], Sukanya Chakrabarti[6], Drona Vargya[2], Nondh Panithanpaisal[2], Arpit Arora[2], Emily Cunningham[7]

[1]Yale University, New Haven, CT, [2]University of Pennsylvania, Philadelphia, PA, [3]Institute for Astronomy, University of Hawaii, Honolulu, HI, [4]University of California- Davis, Davis, CA, [5]University of California Riverside, Riverside, CA, [6]Rochester Institute of Technology, Rochester, NY, [7]Flatiron Institute, New York, NY

The macro-scale properties of dark matter (DM) haloes, such as shape and orientation, rely on the micro-physics of the dark matter particle. Yet the symmetry axes of the Milky Way's dark matter halo are often assumed to be aligned with the symmetry axes of the stellar disc. While this is the likely case for the inner regions of the dark matter halo, there is no physical reason for the outer dark matter halo to have the same alignment. In this work, we explore the evolution of the dark matter halo orientation in the presence or absence of a major merger with a Large Magellanic Cloud (LMC) analog. We restrict our analysis to various simulated Milky Way-mass galaxies ($10^{12} M_\odot$) and their DM haloes from the Latte simulation suite. We present orientations of the dark matter axes relative to the stellar disc axes as a function of radius and as a function of time. We conclude that the orientations of the dark matter halo are divergent from the stellar disc axes beyond the stellar disc (>30 kpc), but this trend is not replicated in simulations with self-interacting dark matter (SIDM). In terms of LMC-host perturbations, we find in-falling LMC satellites have differential effects on the alignment of the disc axes depending on their mass scales. Additionally, there is differential alignment of the halo to LMC analog at the stellar disc and out to the virial radius. Our results indicate a dynamic dark matter halo that is responsive to satellite perturbations and anisotropically aligned to the galactic disc.

Modeling the Response of Dark Matter Halos to Gas Ejection

Zhaozhou Li[1], Avishai Dekel[1,2], Nir Mandelker[1], Jonathan Freundlich[3]

[1]Hebrew University of Jerusalem, Jerusalem, [2]SCIPP, University of California, Santa Cruz, CA,
[3]Observatoire Astronomique, Université de Strasbourg, Strasbourg

We propose an analytic CuspCore model for the response of dark matter (DM) halos to central gas ejection, as a mechanism for generating DM-deficient cores in dwarfs and high-z massive galaxies. We test this model and its other three variants using idealized N-body simulations. The model assumes an instantaneous change of potential, followed by a relaxation to a new Jeans equilibrium. The process turns out to be violent relaxation during the first few orbital periods, followed by phase mixing. By tracing the energy diffusion iteratively, the model reproduces the simulated DM profiles with ~10% accuracy or better. A variant based on adiabatic invariants shows similar precision for moderate mass change but underestimates the DM expansion for strong gas ejection. A variant based on a simple empirical relation between DM and total mass ratios makes slightly inferior predictions. The energy of a shell encompassing fixed DM mass is not conserved under shell crossing, making the earlier version of the CuspCore model (Freundlich+20) underestimate the DM response, which can be partially remedied by introducing an alternative "energy" definition. Our model enables the study of the differential response of a multi-component system of stars and DM in the formation of DM-deficient galaxies.

Can we really pick and choose? Benchmarking various selections of accreted halo stars in observations with simulations

Andreia Carrillo[1], Alis Deason[1], Azadeh Fattahi[1]

[1]Durham University, Durham

Through large spectroscopic surveys providing chemistry for >10^6 stars, and Gaia mapping >10^9 stars in the Galaxy, we have learned that the inner stellar halo is dominated by the accretion of Gaia Enceladus ~10 Gyr ago. With the richness of data at hand, there are a myriad of ways these accreted stars have been selected: from kinematics, to dynamics, to even chemistry. In this work, we explore these different selections and their effects on the inferred progenitor properties (i.e., stellar and total masses) using APOGEE DR17 and Gaia data. Specifically, we investigate the selections made in eccentricity, E-Lz, Vphi-Vr, Jr-Lz, and [Mg/Mn] vs [Al/Fe] and quantify the overlap between and contamination in each selection method. To ultimately understand their efficacy, we apply similar selections in a Milky Way like galaxy with a known Gaia Enceladus progenitor in the AURIGA hydrodynamical simulations and similarly infer progenitor properties. Through this, we aim to understand which selection is best to recover true Gaia Enceladus stars, and how much contamination from other accretion events and from in-situ population is present depending on the selection.

Understanding the Impact of Formation History on the Dynamical Distribution of Substructure using the "Milky Way"-est Simulation Suite

Elise Darragh-Ford[1,2], Philip Mansfield[1], Ethan Nadler[3], Yunchong (Richie) Wang[1], Risa Wechsler[1]

[1]Kavli Institute for Particle Astrophysics and Cosmology and Department of Physics, Stanford University, Stanford, CA, [2]SLAC National Accelerator Laboratory, Menlo Park, CA, [3]Carnegie Observatories, Pasadena, CA

Recent efforts to understand the dynamical history of the Milky Way by exploring the observational signatures of accreted substructure have yielded a number of interesting results. However, it is difficult to interpret the significance of the results in a cosmological context because the unique formation history of the Milky Way can lead to a distribution of substructure which significantly diverges from a typical galaxy of its mass. Here, we attempt to contextualize the impact of the Milky Way's accretion history using the first suite of cosmological zoom-in simulations constrained to resemble the accretion history of the Milky Way (Buch et al., in prep). The suite consists of 25 Milky Way mass host halos (1.0-1.8x10^{12} $M_\odot$) all of which were chosen to have an identified GE and LMC analog. We use detailed particle tracking to trace individual halos down to the simulation resolution limit (~10^{8} $M_\odot$). This allows us to explore in detail the effect these recent mergers have on the anisotropy of the Milky Way's dark matter halo. In addition, combining particle tagging methods with stellar mass estimates from UniverseMachine allows us to study the effects of merger history on phase-space clustering of disrupted substructure. These results can help to understand the robustness and biases of observational studies of phase-space clustering in the stellar halo.

Session: Dynamics Beyond Neptune

The Stability Boundary of the Distant Scattered Disk

Konstantin Batygin[1], Rosemary Mardling[2], David Nesvorny[3]

[1]California Institute of Technology, Pasadena, CA, [2]Monash Univ., Clayton, [3]Southwest Research Institute, Boulder, CO

The distant scattered disk is a vast population of trans-Neptunian minor bodies that orbit the Sun on highly elongated, long-period orbits. The orbital stability of scattered-disk objects (SDOs) is primarily controlled by a single parameter -- their perihelion distance. While the existence of a perihelion boundary that separates chaotic and regular motion of long-period orbits is well established through numerical experiments, its theoretical basis as well as its semimajor axis dependence remain poorly understood. In this work, we outline an analytical model for the dynamics of distant trans-Neptunian objects and show that the orbital architecture of the scattered disk is shaped by an infinite chain of exterior 2:j resonances with Neptune. The widths of these resonances increase as the perihelion distance approaches Neptune's semimajor axis, and their overlap drives chaotic motion. Within the context of this theoretical picture, we derive an analytic criterion for instability of long-period orbits, and demonstrate that rapid dynamical chaos ensues when the perihelion drops below a critical value, given by $q=a_N(\ln((24^2/5)(m_N/M)(a/a_N)^{5/2}))^{1/2}$. This expression constitutes an analytic boundary between the "detached" and actively "scattering" subpopulations of distant trans-Neptunian minor bodies. Additionally, we find that within the stochastic layer, the Lyapunov time of SDOs approaches the orbital period, and show that the semimajor axis diffusion coefficient is approximated by $D_a \sim (8/(5\pi))(m_N/M)(G\,M\,a_N)^{1/2}\exp[-(q/a_N)^2/2]$.

The Stability Boundary of the Scattered Disk: Octupole and Beyond

Matthew Belyakov[1], Konstantin Batygin[1]

[1]California Institute of Technology, Pasadena, CA

Scattered Disk Objects (SDOs) are distant minor bodies outside of the Kuiper Belt on highly eccentric orbits, frequently with perihelia near Neptune's orbit. Their interactions with Neptune can lead to interesting dynamics, with the orbital stability of any given SDO determined by its perihelion distance. Batygin et al. (2021) developed a perturbative approach for scattered disk dynamics, finding that to leading order in the semi-major axis ratio, an infinite series of 2:j resonance chains can model for the dynamics of the scattered disk, with overlaps between resonances driving chaotic motion. In this work we address the limitations of the 2:j resonance model for shorter-period orbits by taking the spherical harmonic expansion for Neptune's gravitational potential to octopole order. We find that while 2:j resonances dominated long-period orbits, for smaller semi-major axes, a chain of 1:j resonances emerges as the primary driver of orbital evolution, with 3:j resonances facilitating a small correction. Applying the Chirikov Criterion, we derive a more complete analytic form for the stability boundary of the scattered disk. Additionally, we determine the boundary between the 1:j and 2:j resonance chains and discuss the behavior at transition between the two regimes.

Secular free inclinations in the main Kuiper Belt.

Brett Gladman[1], Yukun Huang[1], Kathryn Volk[2]

[1]University of British Columbia, Vancouver, BC, [2]University of Arizona, Tucson, AZ

There is a complex inclination structure present in the transneptunian object (TNO) orbital distribution in the main classical belt regions between orbital semimajor axes of 39 and 48 au. The long-term (secular) gravitational effects of the giant planets make the TNO orbits precess, but non-resonant objects maintain a nearly constant ‘free’ inclination I free with respect to a local precession pole. Because of the likely cosmogonic importance of the distribution of this quantity, we tabulate free inclinations for all main-belt TNOs, each individually computed using barycentric orbital elements with respect to each object’s local forced pole. We show that the simplest method, based on the Laplace-Lagrange secular theory, is unable

to give correct forcing poles for objects near the secular resonance, resulting in poorly conserved I free values. We thus implement an averaged Hamiltonian to obtain the expected nodal precession for each TNO, yielding a significantly more accurate free inclination for non-resonant objects. In addition, using 4-Gyr numerical integrations we show that the vast majority (96%) of the classicals have their I free conserved to <1 degree, demonstrating the advantage of using this quantity in studies of the TNO population and primordial inclination profile; our computed distributions only reinforce the idea of a very co-planar surviving 'cold' primordial population, overlain by a large I-width implanted 'hot' population.

The Populations of Plutinos and Other Resonant TNOs in the Distant Solar System

Samantha Lawler[1], Rosemary Pike[2], Mike Alexandersen[3], Breanna Crompvoets[4], Lowell Peltier[5], Kathryn Volk[6]
[1]University of Regina, Regina, SK, [2]Center for Astrophysics | Harvard & Smithsonian, Cambridge, MA, [3]Center for Astrophysics | Harvard & Smithsonian, Cambridge, MA, [4]University of Victoria, Victoria, BC, [5]University of Victoria, Regina, SK, [6]University of Arizona, Tucson, AZ

We have an ongoing survey on the Canada-France-Hawaii Telescope that is targeted toward the off-ecliptic areas where Kozai Plutinos are predicted to be at pericenter and thus easiest to detect. We found fewer Plutinos than we expected, but a larger fraction of potential Kozai Plutinos, showing the power of off-ecliptic measurements for constraining dynamically hot populations in the Kuiper Belt as compared with primarily ecliptic surveys. Our survey also discovered many new TNOs on large semimajor axis orbits. With additional astrometry in the near-future, we expect many of these to be on resonant orbits, because the OSSOS Survey found dozens of TNOs in high-order resonances at very large distances. Because OSSOS was well-characterized, with well-known observational biases, we can measure the debiased orbital distributions and absolute populations in these distant resonances. Our findings are suggestive of ongoing temporary resonant sticking by scattering TNOs. However, the approximately measured population sizes from Survey Simulator modelling are much larger than predicted from the current scattering population size, so the full story of emplacing TNOs into these distant resonances isn't yet clear.

Close enough? How variations in the giant planets' final orbits in migration simulations affect predicted resonant transneptunian populations

Kathryn Volk[1], Arcelia Hermosillo Ruiz[2], Ruth Murray-Clay[2], Rosemary Pike[3]
[1]University of Arizona, Tucson, AZ, [2]University of California, Santa Cruz, Santa Cruz, CA, [3]Center for Astrophysics | Harvard & Smithsonian, Cambridge, MA

The observed populations of transneptunian objects (TNOs) in Neptune's mean motion resonances provide important clues about the nature and extent of giant planet migration in our solar system's early history. To test scenarios for the dynamical histories of the giant planets, we rely on numerical simulations that approximate different migration histories for the planets and track how test particles representing primordial TNOs end up distributed once the giant planets arrive at their final locations. But there remains a question not satisfactorily answered in the current literature: how closely do the end states of the simulated giant planets' orbits need to resemble the orbits of the real, present day giant planets for the simulation to produce acceptably consistent predictions to compare to the real, observed TNO distributions. Modelers typically impose some range in giant planet period ratios and eccentricity ranges in deciding whether a migration simulation output is "acceptable", but how to define this acceptability has not actually been examined in much detail, even in the simplest case of smooth outward giant planet

migration. We will present a suite of smooth planet migration simulations that result in final giant planet orbits with varying levels of fidelity to the current giant planets in terms of orbital period ratios, eccentricity and inclination ranges, and dominant eccentricity and inclination secular modes. By examining the detailed distribution of resonant particles captured in these simulations via resonance sweeping, we can determine which aspects of the final giant planet system architecture are most important to match in migration simulations. We focus on resonance sweeping because it is a very efficient capture mechanism, allowing us to explore a wide range of planet architectures with a large number of captured test particles at relatively modest computational cost. The lessons learned from these simulations can then guide future explorations of the less-efficient resonant capture mechanisms in the more complicated giant planet migration scenarios that are needed to reproduce many of the observed features of the TNO population.

Constraints on Migration Scenarios of Neptune Due to Stochasticity

Arcelia Hermosillo Ruiz[1], Ruth Murray-Clay[1], Kathryn Volk[2], Harriet Lau[3]
[1]University of California, Santa Cruz, Santa Cruz, CA, [2]University of Arizona, Tucson, AZ, [3]UC Berkeley, Berkeley, CA

Observational signatures of outer solar system dynamics that require comparisons across several mean motion resonances (MMRs) in the trans-Neptunian population have been difficult to evaluate in the past due to observational limits. Well-characterized surveys such as the Outer Solar System Origins Survey (OSSOS) and the upcoming LSST provide an opportunity to look across the resonances and improve our understanding of the dynamical history of our solar system, making this an excellent time to be studying cross-MMR signatures. All standard scenarios of Neptune's outward migration have a planetesimal-driven component at the end. Even a gravitational upheaval scenario will experience a planetesimal-driven migration component after some eccentricity damping. During this migration, "graininess" due to the finite sizes of planetesimals leads to imperfect retention of objects in MMRs. We explore how the stochasticity of the planetesimal-driven process limits the possible time spent in this phase of Neptune's dynamical evolution. While noise has been considered in several models, the current literature is missing up-to-date constraints for how long and how far Neptune could have migrated before losing objects in resonance due to stochasticity, as well as constraints on the size distribution of planetesimals present during migration. Understanding the planetesimal-driven component provides a constraint on a unified model that explains MMR occupation over the full range of resonances. In this study, we identify the relative impact of noisy migration on resonance retention for all resonances up to fourth-order lying between the 3:2 and the 3:1, including the 5:2 which hosts a surprisingly large population of objects. Weaker resonances have not been taken into strong consideration in past studies. For a given size distribution of planetesimals, stochasticity is dominated by those with maximum Nm^2 where N is the number of planetesimals and m is the mass of the individual planetesimal, implying that the largest planetesimals primarily drive stochastic loss. We know that the residual planetesimal disk mass is significantly lower than it was before migration, but it is still uncertain what physical processes caused such a substantial depletion of material. We approach this question by finding a maximum constraint on the amount of mass in large (r ~ 800 km) objects during Neptune's era of planetesimal-driven migration and drawing conclusions about the primordial size distribution

Spontaneous Symmetry Breaking in the Primordial Scattered Disk

Alexander Zderic[1], Ann-Marie Madigan[2], Maria Tiongco[2], Angela Collier[2], Heather Wernke[3], Aleksey Generozov[4]
[1]JILA / CU Boulder, Louisville, CO, [2]JILA / CU Boulder, Boulder, CO, [3]University of Mary, Bismark, ND, [4]Technion, Haifa

Self-gravitational, axisymmetric disks of eccentric orbits in near-Keplerian potentials are unstable to an out-of-plane buckling. This spontaneous symmetry breaking appears in Kepler elements as an increase in inclination, a decrease in eccentricity, and a clustering in argument of periapsis. Later, the broken symmetry seeps into the plane of the disk creating a lopsided $m=1$ mode seen as clustering in longitude of periapsis. We discuss the possibility that this instability occurred in the primordial planetesimal population in the early Solar System thus explaining the peculiarities in orbits of the eTNOs and Sednoids.

On the Secular Dynamics of Putative Astrophysical Disk in the Outer Solar System

Arnav Das[1], Konstantin Batygin[2]
[1]California Institute of Technology, Pasadena, CA, [2]California Institute of Technology, North Andover, MA

"The trans-Neptunian scattered disk exhibits unexpected dynamical structure, ranging from an extended dispersion of perihelion distance to a clustered distribution in orbital angles. Self-gravity of the scattered disk has been proposed in the literature as an alternative mechanism to Planet Nine for sculpting the orbital architecture of the trans-Neptunian region. The numerics of this hypothesis hitherto have been limited to N=O(100) super-particle simulations with no resolution of the motion of the giant planets, which are instead captured in the orbit-averaged (quadrupolar) potential through an enhanced J2 moment of the central body. Such simulations reveal the onset of collective dynamical behaviour — termed the "inclination instability" — wherein orbital circularisation occurs at the expense of coherent excitation of the inclination. Here, we report N=O(10^4) GPU-accelerated simulations of a self-gravitating scattered disk (across a range of disk masses spanning 5 Me to 40 Me) that self-consistently account for intra-particle interactions as well as Neptune's perturbations. Our numerical experiments show that even under the most favourable conditions, the inclination instability never ensues; instead, due to scattering, the disk depletes. While our calculations show that a transient lopsided structure can emerge within the first few hundreds of Myr, the terminal outcomes of these calculations systematically reveal a scattered disk that is free of any orbital clustering."

A Rogue Planet Populated the Distant Kuiper Belt

Yukun Huang[1], Brett Gladman[1], Matthew Beaudoin[2]
[1]University of British Columbia, Vancouver, BC, [2]University of British Columbia, North Vancouver, BC

The orbital distribution of trans-Neptunian objects (TNOs) in the distant Kuiper Belt (with semimajor axes beyond the 2:1 resonance, roughly a > 50 au) provides constraints on the dynamical history of the outer solar system. Recent studies have shown two striking features of this region: 1) a very large population of objects in distant mean-motion resonances with Neptune, and 2) the existence of a substantial detached population (non-resonant objects largely decoupled from Neptune). While various Neptune migration models are able to implant some resonant and detached objects during the planet formation era, they fail to match a variety of aspects of the orbital distribution in the distant Kuiper Belt. In this work, we report simulations that are carried out using an improved version of the GPU based code GLISSE (Zhang & Gladman 2022), following 100,000 test particles per simulation in parallel while handling their planetary close encounters. We demonstrate for the first time that a 2 Earth–mass rogue planet temporarily present during planet formation can abundantly populate both the distant resonances and the detached populations, even without any planetary migration. We show how weak encounters with the rogue increase the efficiency of filling the resonances, while also dislodging objects out of resonances at high perihelia. Its secular effect simultaneously generates numerous detached objects observed at all semimajor axes. These results suggest that the early presence of an additional planet reproduces the observed TNO orbital structure in the distant Kuiper Belt.

Session: Mapping and modeling the Milky Way's tidal streams

Unlocking the History of Galaxy Mergers Through the Automated Analysis of Tidal Debris Substructures

Shifra Mandel[1], Kathryn Johnston[2], David Hendel[3]

[1]Columbia University, Brooklyn, NY, [2]Columbia University, New York, NY, [3]University of Toronto, Toronto, ON

Galaxies grow through hierarchical mergers, with high-mass galaxies cannibalizing the satellite dwarf galaxies that orbit them. These galactic accretion events leave behind signatures in the form of tidal debris structures that encode information about their progenitors and hosts. Examining these substructures can open a window into the accretion histories of galaxies in the universe, as well as the dark-matter-dominated mass distribution in galaxy halos. By capturing vast numbers of images of tidal debris substructures, upcoming surveys like LSST will provide us with the data required to gain statistically sound constraints on the orbital distributions of satellites. An automated method for analyzing this data is vital for efficiency and consistency. We present an algorithm that can efficiently and reliably measure the properties of tidal debris substructures, yielding results that can be used to constrain the distributions of accreting satellites. Our method is capable of distinguishing shell-like and stream-like tidal debris – the most distinct morphologies – and measuring their luminosities and scales, properties that hint at the shape of the satellite orbit, the duration of accretion, and satellite mass. We demonstrate our algorithm on snapshot images from n-body simulations, and explore how analyzing their observable properties will help us unravel the accretion histories of galaxies in our universe, and allow us to probe theories of hierarchical galaxy formation and their underlying cosmological paradigm.

The Global Dynamical Atlas of the Milky Way mergers: Processing the ESA/Gaia dataset using state-of-the-art algorithms

Khyati Malhan[1]

[1]MPIA, Heidelberg, Heidelberg

The stellar halo of the Milky Way was predominantly formed by the merging of numerous progenitor galaxies. However, our knowledge of this merging process is still incomplete, especially in regard to the total number of mergers, their global dynamical properties and their contribution to the stellar population of the Galactic halo. In this regard, I will talk about two algorithms, namely **STREAMFINDER** and **ENLINK**, and show their power in detecting and characterizing the Milky Way mergers using the **ESA/Gaia** dataset.

1) **STREAMFINDER** is specially designed to detect stellar streams of the halo. Using **Gaia DR2** and **EDR3**, **STREAMFINDER**has charted more than 40 streams in our Galaxy. I will discuss some interesting dynamical and chemical properties of these streams. [This discussion will be based on our numerous STREAMFINDER-based papers, for instance, https://arxiv.org/abs/2104.09523]

2) **ENLINK** is a group-finding algorithm that we recently employed to analyse the **Gaia EDR3** based orbits of 170 globular clusters, 41 streams and 46 satellite galaxies. We detected 7 mergers: including the previously known "*Sagittarius*", "*Cetus*", "*Gaia-Sausage/Enceladus*", "*LMS-1/Wukong*", "*Sequoia+Arjuna+I'itoi*" and two discoveries - "*Pontus*" and "*Candidate*". I will discuss the properties of these massive mergers and also focus on the most metal-poor merger of our Galaxy (that possess [Fe/H]_minima~ -3.4 dex). [This discussion will be based on our ApJ paper: https://arxiv.org/abs/2202.07660]

Identifying the Multiple Radial Mergers in the Local Stellar Halo with Chemodynamics

Thomas Donlon[1], Heidi Newberg[1]

[1]Rensselaer Polytechnic Institute, Troy, NY

One of the seminal results from the Gaia survey was the discovery that most of the halo stars in the solar neighborhood were on radial orbits. It was conjectured that a large fraction of the halo was composed of one merger event that happened very early in the evolutionary history of the Milky Way, now known as the Gaia-Sausage/Enceladus merger. More recent results have questioned the number of merger remnants that contribute to the radial component of the halo, and also the timing of these infall events, though this remains unresolved. Different papers have assigned different names and used various selection criteria to identify the proposed radial merger events, including different criteria for the Gaia-Sausage/Enceladus merger. We found that dwarf stars within 2 kpc of the Sun separated into at least three components that were distinct in kinematics and photometrically determined metallicity. More recently, we used the dynamics and chemical abundances for APOGEE and GALAH stars within 5 kpc of the Sun to identify the same three distinct components. In the local solar region, the velocity and chemical structures originally attributed to the Gaia-Sausage/Enceladus merger are actually a combination of these three radial components. These mergers include a metal-rich but alpha-poor major merger that is consistent with a recent time of accretion (the Virgo Radial Merger), a metal-rich, alpha-rich, low-energy merger that is consistent with being accreted early on in the Galaxy's history (Cronus), and a metal-poor, alpha-rich component of the halo that is consistent with either a recent major merger or many smaller radial mergers (Nereus).

Too Big to Fail? 6D Stellar Streams in the Milky Way and Cosmological Simulations

Nora Shipp[1]

[1]MIT, Cambridge, MA

Recent large photometric, astrometric, and spectroscopic surveys have enabled the first systematic observations of Milky Way stellar streams in 6D. At the same time, cutting edge cosmological simulations are finally approaching resolutions that allow for the study of dwarf galaxy streams around Milky Way-like hosts. In this talk, I will present the discovery and characterization of a population of 6D stellar streams with observations from the Dark Energy Survey, Gaia, and the Southern Stellar Stream Spectroscopic Survey (S5), and compare this population to streams identified in cosmological simulations. These comparisons enable deeper studies of satellite populations and tidal disruption in simulations and observations, and further tests of the small-scale challenges to LCDM.

Charting the Galactic Acceleration Field with Stellar Streams: A Flexible Model Independent Approach

Jacob Nibauer[1], Miles Cranmer[1], Vasily Belokurov[2], Jeremy Goodman[3], Shirley Ho[4]

[1]Princeton University, Princeton, NJ, [2]University of Cambridge, Cambridge, [3]Princeton Univ. Obs., Princeton, NJ, [4]Flatiron Institution, New York, NY

We present a data-driven method for fully reconstructing the Galactic acceleration field from phase-space measurements of stellar streams. Using a flexible and differentiable neural network that parametrizes the stream in phase space, our approach enables a direct estimation of the acceleration vector along a given stream. The divergence of the acceleration field is constrained to be negative, as required by Poisson's equation for a positive mass density; this yields smoother results. Our approach is unique in that a model for the galactic gravitational potential does not need to be specified beforehand. Our algorithm treats the stream as a collection of tracer particles on locally similar orbits, rather than assuming that the stream delineates any single stellar orbit in the galaxy. Accordingly, our approach allows for distinct regions of the stream to have different energies, as is the case for real stellar streams. Once the acceleration vector is sampled along the stream, standard analytic models for the Galactic potential can then be constrained. Alternatively, we demonstrate that the potential can be represented with a neural network to enable full model flexibility while minimizing non-physical artifacts through Poisson's equation. On mock data, our approach recovers the true potential with sub-percent level fractional errors across a range of scales, providing a new avenue to map the Milky Way with stellar streams.

Using Tidal Streams To Constrain Halo Minor Axis

Nondh Panithanpaisal[1], Robyn Sanderson[1,2]

[1]University of Pennsylvania, Philadelphia, PA, [2]Center for Computational Astrophysics, New York, NY

Recent studies have shown that there is a significant misalignment between the minor axis of the Milky Way (MW) outer halo and the direction perpendicular to the central stellar disk. In this work, we test a method to constrain the minor axis of the host dark matter halo using a set of simulated tidal streams within MW-mass halos from the FIRE cosmological simulations. Our method is complementary to other traditional methods such as orbit fitting. Utilizing angle and frequency variables, we show that we can find a galactic direction that yields minimal offset between the slopes of the line overdensities in these two subspaces, and it is in good agreement with the actual location of the host dark matter halo's minor axis at distance scales comparable to the average distance of stream members. We apply this method to the Sagittarius stream in the MW. We report that the MW halo is prolate (q ~ 0.7 – 0.9) and find evidence that the minor axis of the MW halo lies close to the plane of the stellar disk, in agreement with findings from other work.

Session: Near-Earth Objects: From Asteroids to Meteoroids

Modeling the meteoroid environment far from the ecliptic plane

Althea Moorhead[1]

[1]NASA Marshall Space Flight Center, Huntsville, AL

NASA's Meteoroid Engineering Model (MEM) describes the meteoroid environment encountered by spacecraft in the inner solar system. MEM's algorithms take advantage of the fact that the vast majority of spacecraft remain close to the ecliptic plane in order to make several simplifying assumptions. However, this results in a model that cannot describe the environment for spacecraft such as Ulysses that travel far from the ecliptic, and limits the potential to validate the model using impact signatures from asteroids on inclined orbits. We are in the process of developing a new version of the code, numbered 3.1-alpha, that correctly computes the meteoroid flux and directionality far from the ecliptic. We present a new formulation of the spatial probability distribution function for fully precessed meteoroid models and compare our results with zodiacal light data.

The effects of comet ejection characteristics on meteoroid stream cross-section profiles

Matthew Tiscareno[1], Petrus Jenniskens[1], Jeremie Vaubaillon[2]

[1]SETI Institute, Mountain View, CA, [2]IMCCE, Paris

Leonid storms during the 1998–2002 return exhibited a strongly peaked "Lorentzian" profile as a function of Earth's position in its path around the Sun (Jenniskens 2006, Meteor Showers and their Parent Comets, Cambridge Univ Press, ch.15). That shape and the predicted level of activity for older dust trails does not match simulations of the stream of debris ejected from comet 55P/Tempel-Tuttle by a standard comet ejection model and its subsequent dynamical evolution and interaction with Earth. Possible explanations for the discrepancies include a gradual destruction of larger meteoroids into smaller ones during the time between ejection from the source comet and interaction with Earth, or discrepancies in the comet ejection model.

We have revived the Pintem2 package (Vaubaillon 2005a, 2005b, A&A) for simulating meteoroid trajectories from source comet ejection and forward in time. In this talk, we will show correlations between the along-track profile of various Leonid streams and the time and velocity of each meteoroid's ejection from the source comet. We will investigate whether physically plausible patterns in ejection characteristics can help simulated meteor stream profiles to better match observations.

Obliquity evolution of NEOs due to planetary flybys and YORP

Oscar Fuentes-Munoz[1], Daniel Scheeres[2]
[1]University of Colorado Boulder, Boulder, CO, [2]University of Colorado, Boulder, Boulder, CO

The spin axes and spin rates of near-Earth objects (NEOs) evolve under the influence of gravitational and thermal torques. The Yarkovsky–O'Keefe–Radzievskii–Paddack (YORP) effect tends to drive the obliquities of asteroids to 0 or 180 degrees and speeds up or down their spin rates. However, the orbital plane of asteroids drift because of the gravitational influence of the planets of the solar system and can abruptly change due to close planetary encounters. Therefore, the obliquity, a parameter of the YORP effect, is coupled with the orbital dynamics. On top of this coupling, planetary close encounters can disrupt the spin state of NEOs. In this work we study the spin-orbit problem by modeling together the long-term dynamics of the orbit and YORP while considering the presence of planetary close encounters.

We model the trajectories of NEOs using a semi-analytical propagation tool that combines the two main dynamical effects of secular drift and planetary flybys. First, we use an analytical model of the long-term dynamics as influenced by Jupiter. This leads to a solution of the evolution of the spin state under YORP and the gravitational influence of Jupiter that applies in the absence of planetary close encounters. Then, since we are tracking the trajectory of the asteroid, we detect the close encounters and compute the variation of the orbit elements during close encounters to find their effect on the spin state of the asteroid.

Because of the sensitivity to the initial conditions of the orbits of NEOs, we study the evolution of their orbits and spin states statistically. In this talk we show the results of the study of two types of body, a large asteroid in which the YORP effect plays a small role and the evolution of a small, fast rotator. The semi-analytical propagation allows us to rapidly estimate the trajectories and spin states of individual asteroids, obtaining a statistical representation of their states in the future.

Earth's Quasi-satellite Kamo'oalewa's Possible Origin as Lunar Ejecta

Jose Castro[1], Renu Malhotra[1], Aaron Rosengren[2]
[1]University of Arizona, Tucson, AZ, [2]University of California|San Diego, La Jolla, CA

The most recently discovered quasi-satellite (QS) of the Earth is the near-Earth asteroid Kamo'oalewa (469219), which is exceptional amongst the sparse population of Earth's co-orbitals due to its long-term residence in its current QS state, as well as the long-term persistence of its horseshoe (HS) transitions revealed by numerical simulations. Kamo'oalewa's close proximity to Earth, as well as its unknown dynamical original and physical properties, make this body a scientifically compelling candidate for a future space mission (Venigalla et al. 2017; Jin et al. 2020).

Considering its very Earth-like orbit and its L-type reflectance spectrum, we explore the hypothesis suggested by Sharkey et al. (2021) that it might have originated in the Earth-Moon system as a debris-fragment from a meteoroidal impact with the lunar surface. We carry out numerical simulations, using the open source REBOUND N-body software package, of test particles ejected from the Moon's surface at different locations and with a range of ejection velocities exceeding the lunar escape velocity. We find that most of these ejecta evolve into heliocentric orbits, but a small minority of these ejecta evolve into co-orbital states compatible with Kamo'olewa's dynamical behavior.

Early results from the MEGASIM: Multitudinous Earth Greek (not Trojan) Asteroid SIMulation

Travis Yeager[1]

[1]Lawrence Livermore National Laboratory, Livermore, CA

Presenting early results from the MEGASIM simulations. The dataset consists of two separate large-scale Earth Trojan Asteroid (ETA) n-body simulations built using the IAS15 and Whfast integrators. The MEGASIM simulations consist of 22.4 million initial ETAs and have so far been integrated over a 1 Gyr timescale. ETAs co-orbit the Sun with Earth and remain loosely bound to the fourth or fifth Lagrange points. To date, two ETAs have been detected (2010 TK7 and 2020 XL5); however, based on their orbits, these are likely temporary captures rather than members of a primordial population. The motivation for our simulations is multi-faceted: (1) the lack of a detected population despite literature claims of stability over the age of the Solar System, (2) ETAs are important for both Solar System science and planetary defense, and (3) the proximity of ETAs makes them prime candidates for space exploration missions. These simulations are of extremely high fidelity, large in number and long in simulation time. Covered in this talk will be the lifetimes of ETA orbits, Keplerian orbital evolution and maps of the theoretical observability and spatial distributions.

Limits on Energy and Angular Momentum in the Full N-Body Problem

Daniel Scheeres[1]

[1]University of Colorado Boulder, Boulder, CO

The range of energies and angular momentum that exist for the full N-Body problem when components are resting on each other is studied. Using a simple model of equal sized spheres, lower and upper bounds on a system's energy are found for the collection to remain connected as a single body, up to N=21. The lower bound is developed based on a continuum limit combined with the packing fraction of a granular media. To find the upper bound we use previous results on the existence and stability of a "straight-line" Euler resting configuration of N bodies that represents the extreme limit of a connected single body. Combined, these provide a range of energies and angular momentum values that a collection of N bodies can sustain before the system must fission into two or more components. Connections between these limits and other bounds on full N-body systems are investigated.

Session: Rubin Prize Talk: Ann-Marie Madigan

Eccentric Science

Ann-Marie Madigan[1]

[1]CU Boulder, Boulder, CO

The collective gravity of bodies on eccentric orbits is key to understanding the evolution of gravitational systems from planets to galaxies. In this talk, I will demonstrate wide-ranging implications of these dynamics such as the orbital clustering of icy bodies in the outer solar system, the feeding of stars and gas to supermassive black holes, and surprising locations of galactic dark matter over-densities.

Session: Dynamics Brouwer Prize Talk: Amina Helmi

Dynamics and history of the Milky Way

Amina Helmi[1]

[1]University of Groningen, Groningen

The combination of data from the Gaia mission and from ground-based spectroscopic surveys has been extremely powerful and has led to a revolution in our understanding of the Milky Way. In this talk, I will discuss a few of the recent findings on the dynamics and history of the Milky Way, with particular emphasis on what we have learned about its assembly thus far.

Wednesday April 27

Special Session: Compact Object Binaries I: AGN Disk Environments

SYMMETRY BREAKING IN DYNAMICAL ENCOUNTERS IN THE DISKS OF ACTIVE GALACTIC NUCLEI

Yihan Wang[1], Barry McKernan[2], K.E. Saavik Ford[3], Rosalba Perna[1], Nathan Leigh[4], Mordecai-Mark Mac Low[4]

[1]Stony Brook University, Stony Brook, NY, [2]BMCC-CUNY, New York, NY, [3]Borough of Manhattan Community College - CUNY, New York, NY, [4]American Museum of Natural History, New York, NY

Active galactic nucleus (AGN) disks may be important sites for stellar mass binary black hole (BBH) mergers, but the detailed processes that lead to a BBH merger in an AGN disk are not yet well-constrained. We expect that binary formation in AGN disks is extremely efficient, and that initial binary hardening will occur due to gas drag. However, the gas drag will eventually become inefficient, leading to binaries that stall at semi-major axes too large for a gravitational wave-driven merger to occur in less than the AGN disk lifetime. Thus, dynamical encounters could play a critical role in hardening (or disrupting) binaries in the AGN channel. The imprint of dynamical processes particular to AGN disks could appear in the gravitational wave signal of such BBH mergers.

Most dynamical channels for BBH mergers are rotationally symmetric and therefore predict a symmetric distribution of effective spin around zero. However, there are several natural sources of symmetry breaking in the AGN channel for BBH mergers. We show via numerical experiments with the high-accuracy, high-precision few-body code that broken symmetry in dynamical encounters in AGN disks can lead to an asymmetry between prograde and retrograde BBH mergers. Under the assumption that the spin of the BHs becomes aligned with the angular momentum of the disk on a short timescale compared with the encounter timescale, an asymmetric distribution of effective spin is predicted in LIGO-Virgo detections of BBH mergers from AGN disks.

Long-term Evolution of Tightly-Packed Stellar Black Holes in AGN Disks: Formation of Merging Black-Hole Binaries via Close Encounters

Jiaru Li[1,2], Dong Lai[1], Laetitia Rodet[1]
[1]Cornell University, Ithaca, NY, [2]Los Alamos National Laboratory, Los Alamos, NM

We study the long-term evolution of two or more stellar black holes (BHs) on initially separated but unstable circular orbits around a supermassive BH (SMBH). Such a close-packed orbital configuration can naturally arise from BH migrations in the AGN disk. Dynamical instability of the orbits leads to close encounters between two BHs, during which the BH separation r_{p} becomes less than the Hill radius R_{H}. In the very close encounters (with r_{p} several orders of magnitude less than R_{H}), tight merging BH binaries can form with the help of gravitational wave emission. We use *N*-body simulations to study the time evolution of close encounters of various degrees of "closeness" and the property of the resulting binary BH mergers. For a typical "SMBH + 2 BHs" system, the averaged cumulative number of close encounters (with $r_{\mathrm{p}} \sim\leq R_{\mathrm{H}}$) scales proportional to $t^{0.5}$. The minimum encounter separation r_{p}, which spans several orders of magnitude, follows a linear cumulative distribution $P(<r_{\mathrm{p}})$ that is proportional to r_{p}. From these, we obtain a semi-analytical expression for the averaged rate of binary captures that lead to BH mergers. Our results suggest that close-packed BHs in AGN disks may take a long time ($\geq\sim 10^6$ orbits around the SMBH) to experience very close encounters and form a bound binary, although this time can be much shorter if the initial BH orbits are highly aligned. The BH binary mergers produced in this scenario always have high eccentricities when entering the LIGO band, and have a broad distribution of orbital inclinations relative to the original AGN disk. We also carry out a preliminary exploration on the effects of the gas disk and find that simple gas drags on the BHs do not lead to an enhanced BH binary capture rate.

Blackhole mergers through evection Resonances

Hareesh Gautham Bhaskar[1], Gongjie Li[1], Douglas Lin[2]
[1]Georgia Institute of Technology, Atlanta, GA, [2]University of California, Santa Cruz, Santa Cruz, CA

Mechanisms have been proposed to enhance the merger rate of stellar mass black hole binaries, such as the Von Zeipel-Lidov-Kozai mechanism (vZLK). However, high inclinations are required in order to greatly excite the eccentricity and to reduce the merger time through vZLK. Here, we propose a novel pathway through which compact binaries could merge due to eccentricity increase, including in a near coplanar configuration. Specifically, a compact binary migrating in an AGN disk could be captured in an evection resonance, when the precession rate of the binary equals their orbital period around the supermassive black hole. In our study we include precession to due first-order post Newtonian precession as well as due to a massive disk around one of the components of the binary. Eccentricity is excited when the binary sweeps through the resonance which happens only when it migrates on a timescale 10-100 times the libration timescale of the resonance. Libration timescale decreases as the mass of the disk increases. The eccentricity excitation of the binary can reduce the merger timescale by a factor up to $\sim 10^{3-4}$.

Spin Variations of Black Hole Binaries in AGN Disks

Gongjie Li[1], Hareesh Gautham Bhaskar[1], Bence Kocsis[2], Douglas Lin[3]
[1]Georgia Institute of Technology, Marietta, GA, [2]University of Oxford, Oxford, [3]University of California, Santa Cruz, Santa Cruz, CA

The spin-orbit misalignment of stellar-mass black hole binaries (BHB) provide important constraints on the formation channels of merging BHBs. Here, we study the spin evolution of a black-hole component in a BHB around a supermassive BH (SMBH) in an AGN disk. We consider the BH's spin-precession due to the J_2 moment introduced by a circum-BH disk within the warping/breaking radius of the disk. We find that the BH's spin-orbit misalignment (obliquity) can be excited via spin-orbit resonance between the BHB's orbital nodal precession and the BH spin-precession driven by the circum-BH disk. Assuming a 10^7\msun~SMBH, this typically occurs at a distance of 10^{2-4}AU to the SMBH or $10^{3-5} GM_{\rm SMBH}/c^2$. In many cases, spin-orbit resonance leads to a high BH obliquity, and a broad distribution of the binary components' obliquities and effective spin parameters.

Star-Disk Interactions in Active Galactic Nuclei

Gaia Fabj[1]
[1]University of Heidelberg, Heidelberg

Active Galactic Nuclei (AGN) are fueled by the accretion of a gaseous disk onto the supermassive black hole (SMBH). As stars and stellar remnants in nuclear star clusters (NSCs) are orbiting the SMBH, they repeatedly plunge through the disk and experience a drag force which will eventually drag their orbits into alignment with respect to the plane of the disk. The continuous supply of components of the NSC to the AGN disk provides a population of embedded objects, which can fuel black hole mergers detectable in gravitational waves with LIGO-Virgo and LISA, thus supporting the idea of an AGN channel for gravitational waves. I present results from both analytical (see Fabj et al. 2020: https://ui.adsabs.harvard.edu/abs/2020MNRAS.499.2608F/abstract) and numerical approaches, where for the latter I perform high-resolution N-body simulations using the Nbody6++GPU code. For both analyses I test geometric and Bondi-Hoyle-Lyttleton drag.

Special Session: Compact Object Binaries II: Cluster Environments

Distortion of Gravitational Wave Signals by Astrophysical Environments

Xian Chen[1]
[1]Peking University, Beijing

Measuring the mass and distance of a gravitational wave (GW) source is a fundamental problem in GW astronomy. The issue is becoming even more pressing since LIGO and Virgo have detected massive black holes that in the past were thought to be rare, if not entirely impossible. The waveform templates used in the detection are developed assuming that the sources are residing in a vacuum, but astrophysical models predict that the sources should form in gaseous environments, move with relatively large velocity, or reside in the vicinity of supermassive black holes. In this talk, I will demonstrate how the above environmental factors could dynamically perturb the source, and consequently distort the GW signals. These effects will lead to a biased estimation of the physical parameters of a GW source.

Collisions in a Galactic Nucleus: Implications for Compact Object Formation and Gravitational Wave Sources

Sanaea Rose[1], Smadar Naoz[1], Re'em Sari[2], Itai Linial[2]
[1]University of California, Los Angeles, Los Angeles, CA, [2]The Hebrew University, Jerusalem

Stars and stellar remnants are concentrated in the inner parsec of a galactic center, which harbors a supermassive black hole (SMBH). In this dense environment, compact objects can collide and interact with main-sequence stars, the most populous objects there. I will discuss the implications and applications of collisions in a galactic nucleus (GN). For example, during a collision, a stellar-mass black hole (BH) can accrete mass. Over many collisions, it can grow to ten or a hundred times its initial size. Repeated BH-star collisions therefore represent a formation channel for intermediate-mass black holes (IMBHs), with implications for gravitational wave (GW) sources. In the dense GN environment, BHs and IMBHs can migrate and merge with the SMBH via dynamical friction and two-body relaxation. These frequent events, extreme mass ratio inspirals (EMRIs) and intermediate-mass ratio inspirals (IMRIs), emit GWs. Compact object collisions with stars can also produce electromagnetic signatures. A GN is therefore an ideal environment for the creation of extreme transient events like GW and X-ray sources.

Binary evolution, gravitational-wave mergers and explosive transients in multiple-populations gas-enriched globular-clusters

Mor Rozner[1], Hagai Perets[1]
[1]Technion - Israel Institute of Technology, Haifa

Most globular clusters (GCs) show evidence for multiple stellar populations, suggesting the occurrence of several distinct star-formation episodes. The large fraction of second population (2P) stars observed requires a very large 2P gaseous mass to have accumulated in the cluster core to form these stars. Hence the first population of stars (1P) in the cluster core has had to become embedded in 2P gas, just prior to the formation of later populations. Here we explore the evolution of binaries in ambient 2P gaseous media of multiple-population GCs. We mostly focus on black hole binaries and follow their evolution as they evolve from wide binaries towards short periods through interaction with ambient gas, followed by gravitational-wave (GW) dominated inspiral and merger. We show this novel GW-merger channel could provide a major contribution to the production of GW-sources. We consider various assumptions and initial conditions and calculate the resulting gas-mediated change in the population of binaries and the expected merger rates due to gas-catalyzed GW-inspirals. For plausible conditions and assumptions, we find an expected GW merger rate observable by aLIGO of the order of up to a few tens of $\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$. Finally, our results suggest that the conditions and binary properties in the early stage of GCs could be critically affected by gas-interactions and may require a major revision in the current modeling of the evolution of GCs.

Formation channels of binary black hole mergers in young star clusters

Stefano Torniamenti[1]

[1]University of Padova, Padova

Over the last six years, the LIGO and Virgo interferometers detected an increasing number of gravitational wave events. At the end of the third observing run, the wealth of GW candidates, most of which consist in the merger of binary black holes (BBHs), makes it possible to try to disentangle the formation channels of BBHs, thanks to their peculiar imprints. In particular, the dynamical evolution in stellar clusters leaves a deep imprint on their BBH population, which turn out to present distinctive signatures with respect to the case of isolated evolution.

In my contribution, I will describe the properties of the population of BBH mergers from a new sample of N-body simulations of young star clusters. The simulated stellar systems present fractal initial conditions to mimic the clumpiness of the observed star forming regions and include a realistic primordial population of binaries, characterized by observation-based orbital properties and a mass-dependent binary fraction. Two sets of star are considered to study the evolution of BBHs in stellar environments characterized by different dynamical activity: low-mass clusters (500-800 MSun) and high-mass clusters (5000-8000 MSun). Also, in order to take into account all the possible dynamical effects, the star clusters are evolved for 1500 Myr.

My study shows that the formation channels of BBHs in low-mass and high-mass star clusters are extremely different and lead to two completely distinct populations of BBH mergers. Low-mass clusters host mainly low-mass BBHs born from binary evolution, while BBHs in high-mass clusters are relatively massive (with chirp masses up to 50 MSun) and driven by dynamical exchanges.

Also, high-mass clusters produce a non-negligible number of BBH mergers with primary mass in the pair-instability mass gap, all of them born via stellar collisions, in which a main-sequence star merges with a more evolved star. A fraction of these massive BBHs also leave a merger remnant in the intermediate-mass BH range. These differences are crucial for the interpretation of the formation channels of gravitational-wave sources.

Distinguishing Dynamical Formation Channels Apart Using Burst Timing

Johan Samsing[1]

[1]Niels Bohr Institute, Copenhagen

Eccentricity has over the past couple of years been established as a key indicator of dynamical formation of black hole mergers. However, all dynamical channels give rise to eccentric sources, from single-single captures in galactic nuclei to few-body formation in globular clusters. This opens up a new challenge, namely, how do we distinguish dynamical formation channels apart when they give rise to the same "unique" observables? In my talk I will illustrate that eccentric sources formed through few-body interactions will show a clear time shift in their burst phase due to tidal and relativistic effects, which naturally is not present in e.g. the single-single capture case and for KL-sources. This is likely the only way to tell the difference between dynamical channels case by case, and opens therefore up for a wide range of new possibilities. I will discuss for which systems such time shift observations are possible, and the prospects for 3G observatories.

Session: Dynamical Interactions in Multi-Planet Systems

Edge-of-the-Multis: Evidence for Truncation of the Outer Architectures of Compact Multiple-Planet Systems

Sarah Millholland[1], Matthias He[2], Jon Zink[3]
[1]Princeton University, Princeton, NJ, [2]The Pennsylvania State University, State College, PA, [3]Caltech, Pasadena, CA

Although the architectures of compact multiple-planet systems are well-studied, little has been examined about their "outer edges", or the locations of the outermost planets in these systems. Here we present evidence that the observed high-multiplicity Kepler systems truncate at smaller orbital periods than can be explained by geometric and detection biases alone. To show this, we considered the existence of hypothetical planets orbiting beyond the observed transiting planets with periods and radii dictated by the expected "peas-in-a-pod" patterns. We evaluated the detectability of these hypothetical planets using (1) a novel approach for estimating the mutual inclination dispersion of multi-transiting systems based on transit chord length ratios and (2) a model of transit probability and detection efficiency that accounts for the impacts of planet multiplicity on transit detections. We find that at least ~40% of Kepler compact multis would be expected to show an additional transiting and detected planet orbiting beyond the known planets, constituting a ~7-sigma discrepancy with the lack of such detections. These results can be explained by a decrease in planet occurrence in the outer regions of compact multis (a.k.a. an "edge-of-the-multis"). However, our results can also be reconciled by a significant breakdown of the "peas-in-a-pod" patterns at longer periods, in the form of systematically smaller planet radii or larger period ratios. We discuss the implications and theoretical interpretations of our results for the formation and dynamical evolution of compact multi-planet systems.

Stable or Not: Constraining the Stability of Hidden Super-Short Period Planets

Thea Faridani[1]
[1]University of California Los Angeles, Los Angeles, CA

Recent ground and space-based observations show that stars with multiple planets are common in the galaxy. Most of these observational methods are biased toward detecting large planets near to their host stars. Because of these observational biases, these systems can hide small, close-in planets inward of observed planets. These hidden planets are influenced dynamically by their companions. In certain configurations, this influence can destabilize the system; in others, the star's gravitational influence through both general relativity and the stellar gravitational quadrupole moment (J2) can instead further stabilize (and in some cases, J2 can destabilize) the system. We derive criteria for hidden planets orbiting within known planets that quantify how strongly general relativistic and J2 effects can stabilize systems that would otherwise be unstable. Furthermore, we show the regions of parameter space that possible hidden planets lie in if they are to be stable.

An In-Situ Formation Model for Systems of Tightly-Packed Inner Planets

Spencer Wallace[1], Thomas Quinn[1]
[1]University of Washington, Seattle, Seattle, WA

Using high-resolution N-body simulations, we investigate the outcome of terrestrial planet formation at short (< 100 day) orbital periods under a migration-free model. The collisional and dynamical evolution of systems of nearly 10^6 self-interacting planetesimals are directly followed through the final planet assembly phase. This is done by first modeling the planetesimal evolution with the tree-based N-body code ChaNGa, and then passing the results to the hybrid-symplectic N-body code genga, once the particle count has dropped sufficiently. Previously, we showed that oligarchic growth fails to operate at arbitrarily short orbital periods. This leaves a distinct feature in the mass and orbital distribution of the planetary embryos. In this most recent work, we explore whether this boundary between oligarchic and non-oligarchic growth leaves any kind of imprint on the terrestrial planets that form. If so, this would provide an important clue to evaluate whether migration played a significant role in shaping the architecture systems of tightly-packed inner planets.

Rapid Dynamical Chaos in a Short Period Multi-planet System

M. Ryleigh Davis[1], Konstantin Batygin[1], Juliette Becker[2]
[1]California Institute of Technology, Pasadena, CA, [2]Caltech, Pasadena, CA

The long-term dynamical evolution of the solar system is known to be stochastic, with a characteristic Lyapunov time scale of ~5 Myr. Over the course of the last decade, the tally of chaotic planetary systems has grown, with detailed characterization of orbital evolution of the GJ876 and Kepler-36 systems revealing chaotic phenomenon on ~decadal timescales. In this work, we quantify the dynamics of the seemingly benign architecture of the TOI-125 planetary system which is characterized by eccentricities that are unusually large for a short period super-Earth multi-planetary system. We quantify the dynamics of this system using N-body simulations and find that both the MEGNO and Lyapunov chaos indicators reveal that this system exhibits rapid dynamical chaos. Additionally, we consider long term implications of tidal evolution and its effects on the large-scale architecture of this remarkable system.

Dynamics of Colombo's Top: Non-Trivial Oblique Spin Equilibria of Super-Earths in Multi-planetary Systems

Yubo Su[1], Dong Lai[1]
[1]Cornell University, Ithaca, NY

Many Sun-like stars are observed to host close-in super-Earths (SEs) as part of a multi-planetary system. In such a system, the spin of the SE evolves due to spin-orbit resonances and tidal dissipation. In the absence of tides, the planet's obliquity can evolve chaotically to large values. However, for close-in SEs, tidal dissipation is significant and suppresses the chaos, instead driving the spin into various steady states. We find that the attracting steady states of the SE's spin are more numerous than previously thought, due to the discovery of a new class of "mixed-mode" high-obliquity equilibria. These new equilibria arise due to subharmonic responses of the parametrically-driven planetary spin, an unusual phenomenon that arises in nonlinear systems. Many SEs should therefore have significant obliquities, with potentially large impacts on the physical conditions of their surfaces and atmospheres.

Two Case Studies of Warm Jupiters Suggesting Different Origins

Jiayin Dong[1], Chelsea Huang[2], Rebekah Dawson[1], George Zhou[2], The NEID Science Team[1], TESS Follow-up Observing Program (TFOP)[3], The MINERVA-Australis Team[2], Joseph Rodriguez[4], Jason

Eastman[5], Karen Collins[5], Samuel Quinn[5], Avi Shporer[3], Amaury Triaud[6], Songhu Wang[7], Thomas Beatty[8], Jonathan Jackson[1], Gudmundur Stefansson[9], Andrew Vanderburg[3], Adam Kraus[10], Stephanie Douglas[11], Elisabeth Newton[12], Rayna Rampalli[13], Daniel Krolikowski[14], Dax Feliz[15]
[1]Pennsylvania State University, University Park, PA, [2]University of Southern Queensland, Toowoomba, [3]MIT, Cambridge, MA, [4]Michigan State University, Holt, MI, [5]Center for Astrophysics | Harvard & Smithsonian, Cambridge, MA, [6]University of Birmingham, Birmingham, [7]Indiana University, Bloomington, IN, [8]University of Arizona, Tucson, AZ, [9]Princeton University, Princeton, NJ, [10]University of Texas, Austin, Austin, TX, [11]Lafayette College, Easton, PA, [12]Dartmouth College, Hanover, NH, [13]Dartmouth College, Sacramento, CA, [14]University of Texas at Austin, Austin, TX, [15]Vanderbilt University, Nashville, TN

Warm Jupiters with extreme eccentricities or young ages are ideal test cases to examine the high-eccentricity tidal migration, disk migration, and in-situ formation origins of Warm Jupiters. We present two case studies of TESS Warm Jupiters and their follow-up observations using the CHIRON, Minerva-Australis, and NEID. The first has a super-eccentric orbit, analogous to HD 80606b, and is likely on the high-eccentricity tidal migration track. The second, at only a few hundred Myr old, has a nearly circular and aligned orbit. This latter planet is unlikely to have undergone high-eccentricity tidal migration; instead, it is likely to have originated via disk migration and/or in-situ formation. Two case studies might suggest multiple origins of Warm Jupiters.

Session: History of the Early Solar System

Mercury and the inner solar system sculpted by Earth and Venus' outward migration

Matthew Clement[1], Sean Raymond[2], John Chambers[1]
[1]Carnegie Earth and Planets Laboratory, Washington, DC, [2]Laboratoire d'astrophysique de Bordeaux, Bordeaux

The inner solar system's modern orbital architecture provides inferences into the time of terrestrial planet formation; a ~100 Myr epoch of planet growth via collisions with planetesimals and other proto-planets. While classic numerical simulations of this scenario adequately reproduced the correct number of terrestrial worlds, their semi-major axes and approximate formation timescales, these models were unable to replicate the Earth-Mars and Venus-Mercury mass ratios (~9 and 15, respectively). At present, a number of independent models are capable of consistently generating Mars-like planets and simultaneously satisfying various important observational and geochemical constraints. With the ``small Mars problem'' reduced to a debate over the efficacy of different models, the formation of the solar system's smallest planet has increasingly been the focus of recent theoretical investigations. I will present new results from a collection of companion studies designed to identify viable formation models capable of consistently generating Mercury-like planets. In particular, I will introduce a model where proto-Earth and proto-Venus initially form in the vicinity of Mercury's modern orbit before migrating outward due to interactions with the primordial nebular gas. In successful simulations, Earth and Venus accrete excessive material from the Mercury-region as they migrate, thus allowing a small Mercury to form in dynamical isolation from the other terrestrial worlds. In addition to explaining the precise masses and orbits of all four inner planets, our model is capable of replicating differences between the inferred isotopic compositions of Earth and Mars.

Effects of Jupiter large scale gas-driven migration on the inner solar system

Rogerio Deienno[1], André Izidoro[2], Alessandro Morbidelli[3], David Nesvorny[1]

[1]Southwest Research Institute, Boulder, CO, [2]Rice University, Houston, TX, [3]CNRS, Nice

It has been proposed that Jupiter in our solar system formed at larger distances from the Sun and migrated inwards. Thesedynamical models have been successful in explaining, among other features, the compositional diversity of the main asteroid belt (MAB), the capture of Jupiter Trojan asteroids, and how water was delivered to Earth. Yet, due to computational costs, simulations modeling the effects of Jupiter's gas-driven migration on the inner solar system have mostly neglected collisional evolution of small bodies. In this work we study the implications of large-scale and inward radial migration of Jupiter for the inner solar system while considering the effects of collisional evolution of planetesimals. We use analytical prescriptions to simulate the growth and migration of Jupiter in the gas disk. The planetesimal disk interior to Jupiter's original orbit is attributed an initial total mass and size frequency distribution (SFD). Planetesimals feel the effects of aerodynamic gas drag and once shepherded by the migrating Jupiter collide with one another. We focus our study on the evolution of the SFD of such planetesimal populations, on the amount of mass implanted into the MAB, and on the amount of dust generated via collisions. We find that the SFD implanted into the MAB tends to resemble that of the original planetesimal population interior to Jupiter. We also find that unless very little or no mass existed between 5 au and Jupiter's original orbit, it would be difficult to reconcile the current low mass of the MAB with the possibility that Jupiter migrated from distances beyond 15 au. Finally, we discuss the implications of our results in terms of dust production to the so-called NC-CC dichotomy.

Venus: What does it mean to have no moon

Seth Jacobson[1]

[1]Michigan State University, East Lansing, MI

Venus doesn't have a moon, yet large impacts on terrestrial planets typically generate circumplanetary disks from which moons would accrete. Using numerical simulations, we explore under what conditions moons from giant impacts would not survive. Alternatively, new ideas to grow Venus without giant impacts via pebble accretion must be balanced with the need for a giant impact on Earth. Turning again to numerical simulation, we test the validity of this idea and describe the conditions for which it can be true. Lastly, we propose geochemical tests that can differentiate between these two hypotheses.

Thursday April 28

Session: Galactic Bars

Constraining the length and pattern speed of the Milky Way bar from direct orbit integration

Maddie Lucey[1], Sarah Pearson[2], Jason Hunt[3], Keith Hawkins[4]

[1]University of Texas at Austin, Austin, TX, [2]New York University, New York, NY, [3]Flatiron Institute, New York, NY, [4]University of Texas, Austin, Austin, TX
The dynamics of the inner Galaxy contain crucial clues for untangling the evolutionary history of the Milky Way. However, the gravitational potential of the inner Galaxy is poorly constrained, partly because the precise structure of the Galactic bar is unknown. Specifically, the length of the Galactic bar is currently under debate with length estimates ranging from 3.5-5 kpc. Here, I present a novel method for constraining the length and pattern speed of the Galactic bar using the 6D phase space information of ~210,000 stars from Gaia/APOGEE to directly integrate orbits of Milky Way bar stars. First, I use N-body simulations to validate the method, and then I apply it to APOGEE DR17 and Gaia eDR3 data. I find that the orbit-derived bar length is self-consistent with the potential's bar length only when the structure of the gravitational potential is similar to the N-body model from which the initial positions and velocities of the stars are taken. When I apply the method to the observed data, I expect to find a self-consistent bar length only for a potential that is representative of the APOGEE and Gaia data, i.e., the actual Galactic bar mass distribution. With my method, I can test a variety of potential models and determine which potentials best fit the observed data for the Galactic bar. In this talk, I will present new constraints on the length and pattern speed of the Galactic bar and the potential of the inner Galaxy.

Bar Formation and Destruction in the FIRE2 Simulations.

Sioree Ansar[1,2], Robyn Sanderson[3], Sarah Pearson[4]
[1]CCA, Flatiron Institute, New York City, [2]Indian Institute of Astrophysics, BENGALURU, [3]University of Pennsylvania, Philadelphia, PA, [4]New York University, New York, NY

Despite decades of research, the mechanism by which bars form in galaxies is still a subject of debate. Studies using isolated galaxy evolution simulations have explored different formation mechanisms in controlled simulations with fine-tuned initial conditions. However, galaxies in the Universe evolve in a much more complex environment: they undergo multiple satellite interactions, mergers, gas accretion events, and star formation while simultaneously interacting with their dark matter halo. Past studies have also shown that bars can direct material into the central supermassive black hole in a galaxy, coupling bar formation to black hole feedback. Thus, investigating bar formation and reproducing their observed properties in cosmological simulations is an important step in understanding galaxy formation.

In this work, we look at the 13 high resolution Milky Way mass galaxies from the zoomed-in cosmo-hydro simulation FIRE2 (Feedback in Realistic Environments) suite to first ask: How do bars form and when does bar formation fail? We find examples where bars form due to satellite interactions and others where bars form secularly in the disk. We observe that gas infall and outflow, catalyzed by starburst events, make the disk less likely to host a bar. Particularly, the stellar feedback prescription in FIRE2, and the lack of a prescription for black hole feedback to mitigate the amount of gas in the galaxy centre, together make the disk kinematically hot, such that bars that do form are relatively short and rotate slowly relative to a fast bar having similar length. We verify predictions from controlled simulations for the influence of the disk mass fraction on bar length and shape: when a disk is dominated by baryons up to a large radius, the bar is weak and elliptical in its face-on view. As the disk becomes more dark matter dominated towards the centre, the bar morphology transforms from weak elliptical to a more rectangular and stronger bar.

Our work helps understand the complex mechanism of bar formation in Milky Way type galaxies in a cosmological environment. In contrast with the Auriga and Illustris simulations, which use a different feedback model, FIRE2 galaxies tend to be more disk-dominated, which gives rise to shorter bars.

Resonance Sweeping in Barred Galaxy Simulations

Binod Bhattarai[1], Jason Hunt[2], Sarah Pearson[2], Sarah Loebman[1], Kathryne Daniel[3], Rachel McClure[4]
[1]University of California, Merced, Merced, CA, [2]Flatiron Institute, New York, NY, [3]Bryn Mawr College, Glen Mills, PA, [4]University of Wisconsin -- Madison, Madison, WI

Theory suggests that galactic bars spin down throughout their evolution due to an angular momentum exchange with the inner parts of their dark matter halos. As opposed to a bar with a fixed pattern speed, Chiba et al. (2019) proposed that 'resonance sweeping' due to a decelerating galactic bar can explain local kinematic substructure in the solar neighborhood, like the Hercules stream. To date, resonance sweeping - a process of trapping and dragging the orbits of stars - has been explored both analytically and with test particle simulations that lack self-gravity. Here, we take such analyses a step further and examine resonance sweeping with a high resolution (~10^9 particle) self-consistent N-body simulation. Like Chiba et al. (2019), the bar patten speed in our adopted simulated galaxy slowly decelerates over the course of the simulation, with Ω_{bar} decreasing from 49.88 to 28.84 $kms^{-1}kpc^{-1}$ in 4 Gyr ($\Delta\Omega_{bar}/\Delta t$ = 5.25 $kms^{-1}kpc^{-1}Gyr^{-1}$). For our preliminary test, we calculated frequencies of the stars using AGAMA. We identify stars in Corotation Resonance and Outer Lindblad Resonance and find a significant number of stars remain in resonance later in time suggesting resonant sweeping of orbits due to the decelerating bar. This result in a more realistic, self-gravitating disk indicates that the method of resonance sweeping can indeed be applied to Gaia data.

Deprojection and dynamical modeling of barred galaxies

Shashank Dattathri[1], Monica Valluri[1], Vance Wheeler[1], Eugene Vasiliev[2]
[1]University of Michigan, Ann Arbor, Ann Arbor, MI, [2]Institute of Astronomy, University of Cambridge, Cambridge

We present a parametric method to construct the 3D density distribution of barred galaxies from their surface brightness distributions, which is then used for dynamical modeling using the Schwarzschild orbit superposition method. N-body simulations and observations of barred galaxies show a distinct X or peanut (X/P) shape in the central regions, which is usually attributed to bar buckling and resonance orbit trapping. We model this peanut shape by varying the vertical scale height of the bar across the major axis. We analyze a suite of N-body simulations of barred galaxies to obtain mock photometric data, which we perform the deprojection on to recover the 3D density. We verify the accuracy of our fit by comparing the gravitational potential and forces of the deprojected model and the N-body snapshot, and find reasonable agreement between them. The deprojected density and potential are then used to construct a dynamical model of the galaxy using the FORSTAND code, which implements the Schwarzschild algorithm. An accurate model of the bar, including the X/P shape, is required to construct the gravitational potential of the galaxy, and we highlight the advantages of our method compared to the standard approach of using multi-gaussian expansion (MGE).

Are dark gaps in barred galaxies a signature of bar corotation?

Elena D'Onghia[1], Dhanesh Krishnarao[2], Zachary Pace[1], Alfonso Aguerri[3], Rachel McClure[1], Thomas Peterken[4], Jose Fernandez-Trincado[5], Michael Marrifield[4], Karen Masters[6], Luis Garma-Oehmichen[7], Nicholas Boardman[8], Bershady Matthew[1], Niv Drory[9], Richard Lane[10]
[1]University of Wisconsin, Madison, Madison, WI, [2]Colorado College / Johns Hopkins University, Baltimore, MD, [3]Instituto de Astrofisica de Canarias, La Laguna, [4]University of Nottingham, Nottingham, [5]Centro de Investigacion en Astronomia, Santiago, [6]Haverford College, Haverford, PA, [7]UNAM, Mexico City, [8]University of Utah, Salt Lake City, UT, [9]University of Texas, Austin, TX, [10]Universidad de Concepcion, Concepcion

Stellar bars in galaxies induce morphological features, such as rings, through their resonances. Previous studies suggested that the presence of `dark-gaps' around the stellar bars, regions of the disk where the difference between the surface brightness along the bar major axis and along the bar minor axis are maximal, can be attributed to the location of bar corotation. Here, we test this claim using GALAKOS, a high-resolution N-body simulation of a barred galaxy. Contrary to previous work, our results indicate that `dark gaps' are a clear sign of the location of the 4:1 ultra-harmonic resonance instead of bar corotation. We show that measurements of the bar corotation can indirectly be inferred using kinematic information, e.g., by measuring the shape of the rotation curve. We demonstrate our concept on a sample of 578 face-on barred galaxies in MANGA with both imaging and integral field observations and find the galaxies sample likely consists primarily of fast bars.

Session: Numerics and Methods for Planetary Dynamics

A new method of searching for ghost families in the asteroid belt

Stanley Dermott[1], Dan Li[2], Apostolos Christou[3]
[1]University of Florida, Gainesville, FL, [2]NSF's NOIRLab, Tucson, AZ, [3]Armagh Observatory, UK, Armagh, Northern Ireland

Asteroid families have been discovered by searching for clusters in proper orbital element space using the Hierarchical Clustering Method (HCM). However, this method is limited by the fact that some families overlap in that space. Because of this unavoidable limitation only about half the asteroids in the inner belt with absolute magnitude, $H < 16.5$ are recognized as belonging to distinct families. The remaining asteroids are currently designated as non-family. The number of distinct families has a direct bearing on the number of distinct sources of meteorites and near-Earth asteroids and our understanding of the origin and dynamical evolution of those bodies, and of the asteroid belt itself, is not complete without an understanding of the origin of the non-family asteroids. Here, we present a new method of searching for families that is supplementary to the HCM and has the potential of separating comparatively young families associated with compact clusters in orbital element space from old ghost families with dispersed orbital elements. This supplementary method is based on the idea that, because of orbital evolution due to Yarkovsky forces and other mechanisms, old ghost families should have lower number densities and be comparatively deficient in small asteroids. Hence, by mapping the asteroid number density in orbital element space and comparing that distribution with a map showing the distribution of the slopes of the size-frequency distributions (SFD), we can detect the likely locations of ghost families. Maps for the asteroids in the inner main belt are shown below. Asteroids in ghost families exist in those regions that have both a low number density and a low SFD slope. In the inner main belt, putative ghost families are found predominantly in the region of high orbital inclinations that is bounded by two major resonances. Results will be presented for other regions of the main belt.

A machine-generated catalogue of Charon’s craters and implications for the Kuiper belt

Mohamad Ali-Dib[1]
[1]CAP3/NYU, Abu Dhabi

We investigate Charon's craters size distribution using a deep learning model. This is motivated by the recent results of Singer+2020 who, using manual cataloging, found a change in the size distribution slope of craters smaller than 12 km in diameter, translating into a paucity of small Kuiper Belt objects. Our MaskRCNN-based ensemble of models was trained on Lunar, Mercurian, and Martian crater catalogues and both optical and digital elevation images. We use a robust image augmentation scheme to force the model to generalize and transfer-learn into icy objects. With no prior bias or exposure to Charon, our model find best fit slopes of D$^{-1.28\pm 0.026}$ for craters smaller than 11 km, and D$^{-2.22\pm 0.039}$ for larger craters. These values are consistent with \cite{singer} and thus independently confirm their conclusions.

A Statistical Approach to Optimizing Orbit Constraints for Directly Imaged Exoplanets

William Oldroyd[1], Tyler Robinson[1]
[1]Northern Arizona University, Flagstaff, AZ

Direct imaging capabilities for exoplanets are rapidly increasing. Space telescope concepts, such as HabEx and LUVOIR, have the potential to make a dramatic leap forward in this field with the resolving capability to image Earth analogues around Solar type stars. In the 2020 Decadal Survey on Astronomy and Astrophysics, direct imaging of Earth-like worlds around nearby stars was recommended as the top science priority for future space-based missions. These advances will be made possible through sophisticated starshade and/or coronagraph configurations. One major constraint on the effectiveness of these mission concepts is the amount of time that will be spent on orbital characterization follow-up observations. These observations are expected to take a large fraction of the total observing time for each mission, hence, by reducing the time required to constrain exoplanet orbits, we effectively increase time available to characterize the planets themselves (e.g., determine habitability, etc.).

We have developed a statistical method utilizing Markov Chain Monte Carlo sampling techniques combined with orbital integration to dramatically improve orbit characterization time for directly imaged exoplanets. In this method, we find a best fit orbit for existing observations and assume that the real orbit is reasonably close to this fit. Then we make synthetic observations at regular intervals, each a set fraction of the predicted orbital period of the planet. Over all synthetic observations we use an orbital constraint metric to determine the expected location and corresponding time at which orbit uncertainties are minimized. This provides the optimum revisit time at which to observe the system, thus reducing observational degeneracies and, consequently, the number of observations required to constrain the orbit to within acceptable limits. We find that this method yields dramatic improvement in orbit characterization over previously suggested equal timing observations, as well as, other optimization algorithms we tested.

Stepsize errors in the N-body problem: discerning Mercury’s true possible long-term orbits

David Hernandez[1], Sam Hadden[2]
[1]Center for Astrophysics | Harvard & Smithsonian, Cambridge, MA, [2]Center for Astrophysics | Harvard & Smithsonian, Somerville, MA

Numerical integrations of the Solar System have been carried out for decades. Their results have been used, for example, to determine whether the Solar System is chaotic, whether Mercury's orbit is stable, or to help discern Earth's climate history. We argue that all of the past studies we consider in this work are affected by numerical chaos to different degrees, affecting the possible orbits and instability probability of Mercury, sometimes significantly. We show how to eliminate the effects of numerical chaos by resolving Mercury's pericentre passage. We also show that several higher order symplectic maps do not exhibit significant differences in resolving pericentre passage of Mercury (at fixed time step), making their advantages suspect for calculating long-term orbits. Resolving pericentre passage affects a wide array of orbital numerical studies, like exoplanet studies, studies of the galactic centre, and other N-body problems.

Celestial mechanics with the celmech code

Sam Hadden[1], Daniel Tamayo[2], David Hernandez[3]
[1]CITA, Toronto, ON, [2]Princeton University, Princeton, NJ, [3]Center for Astrophysics | Harvard & Smithsonian, Cambridge, MA

I will introduce "celmech", a new publicly available open-source python package for performing celestial mechanics calculations by constructing, manipulating, and integrating perturbative models for planetary systems' dynamics. While direct numerical integrations with modern computers have largely replaced the need for highly precise perturbative calculations, classical perturbation theory still plays an important role in modern planetary dynamics by providing simplified models for a variety of complex phenomena including mean motion resonances, secular evolution, and dynamical chaos. Classical perturbation theories in planetary dynamics can be elegantly formulated using a Hamiltonian framework, but non-experts (and experts alike) can quickly get mired in the complexities of computing disturbing function expansions and Laplace coefficients. The celmech code automatically computes and evaluates disturbing function coefficients, allowing users to quickly and easily construct Hamiltonian models by adding disturbing function terms with any desired cosine arguments. The code also interfaces closely with the popular REBOUND N-body integrator so that users can easily compare perturbative models against direct N-body integrations. I will give an overview of the code and highlight some example applications. The code can be downloaded at github.com/shadden/celmech.

Celmech II: A universal integrable model for mean motion resonances in closely packed systems

Daniel Tamayo[1], Samuel Hadden[2]
[1]Princeton University, Princeton, NJ, [2]CITA, Toronto, ON

Our analytical understanding of the dynamics between a co-planar pair of planets in mean motion resonances (MMRs) typically relies on models involving a single cosine term in the classical disturbing function expansion, e.g., the pendulum model and the 'second fundamental model for resonance'). This falls out naturally at leading order in the eccentricities in the circular restricted three-body problem, i. e., when one body is a test particle.

A complication in the general case of two massive planets is that there are always multiple strong cosine terms near a given MMR involving different combinations of the two orbits' pericenters. An important, long-standing result is that for first-order (j:j-1) MMRs, it is possible to combine these cosine terms into one through a rotation of variables, and recover the simple integrable models mentioned above. To my knowledge this is a coincidence, in the sense that it is not rigorously extendable to higher order MMRs.

Additionally, different j:j-1 MMRs have different Fourier amplitudes with no obvious relationship to one another.

In the limit where the two planetary orbits are very close to one another (Hill's approximation), there is an additional conserved quantity in the problem, which can be thought of as a center-of-mass eccentricity vector. Hadden (2019) realized that this implies that in the coplanar problem, all MMR cosine terms should be collapsible into a single term. He additionally showed that while this is not rigorously true at wider separations, it is true to excellent approximation for MMRs closer than the 2:1.

We will explore the valuable physical intuition this simplifying approximation provides, and how that can guide our naming and thinking about the various dynamical variables and conserved quantities in the general MMR problem. We also show how thinking about the problem in the tightly spaced limit motivates a natural, universal definition of variables in which all MMRs of a given order share the same Fourier amplitude to lowest order in the eccentricities.

We are implementing these transformations in the open-source celmech package to easily go back and forth with orbital elements / N-body integrations.

Session: Planetary Rings

Using disk structures as historical records: A case study involving Saturn's rings.

Matthew Hedman[1], Philip Nicholson[2], Maryame El Moutamid[2]

[1]University of Idaho, Moscow, ID, [2]Cornell University, Ithaca, NY

Dense disks like Saturn's rings contain spiral structures known as density waves that are generated by mean-motion resonances with external gravitational perturbations from satellites or structures inside the planet. Classic density-wave theory assumes that these gravitational perturbations have a fixed rotation period, but this is not a valid assumption for certain satellites on time-variable orbits and some of the anomalies in Saturn's gravitational field. We have therefore developed semi-empirical extensions of density wave theory that can account for perturbations with time-variable periods and amplitudes. These new models reveal that the observed properties of these structures encode information about how the rotation rates and amplitudes of the relevant gravitational anomalies have changed over time. Indeed, analyses of selected density waves in Saturn's rings demonstrate how these features can be used to trace the history of changes in satellite's orbit periods and the planet's internal structure over several decades. These insights may be useful for interpreting structures in other disks subject to time-variable perturbations.

Ring Seismology of the Ice Giants Uranus and Neptune

Joseph A'Hearn[1], Matthew Hedman[1], Christopher Mankovich[2], Hima Aramona[3], Mark Marley[4]

[1]University of Idaho, Moscow, ID, [2]Caltech, Pasadena, CA, [3]Reed College, Portland, OR, [4]Lunar and Planetary Laboratory, Tucson, AZ

We assess the prospect of using ring seismology to probe the interiors of the ice giants Uranus and Neptune. We do this by calculating normal mode spectra for different interior models of Uranus and Neptune using the stellar oscillation code GYRE. These spectra provide predictions of where in these planets' ring systems the effects of interior oscillations might be detected. We find that f-mode resonances with azimuthal order m equal to 2 or between 7 and 19 fall among the inner rings (6, 5, 4, alpha, and beta) of Uranus. We also find that g-mode resonances may fall among the narrow rings of both planets. Although an orbiter is most likely required to confirm the association between any waves in the rings and planetary normal modes, the diversity of normal mode spectra implies that identification of just one or two modes in the rings of Uranus or Neptune would eliminate a variety of interior models, and thus aid in the interpretation of Voyager observations and future spacecraft measurements.

The motion of satellite self-gravity wakes under the effects of tidal forces and shear: a case study of the Rings of Saturn.

Daniel Sega[1], Glen Stewart[1], Larry Esposito[1]
[1]University of Colorado, Boulder, Boulder, CO

Elongated aggregates of the order of a Toomre wavelength have been known to exist in the denser rings of Saturn. They occur in the A and B ring at distances from Saturn where the average particles are not big enough to fill their Hill sphere, and they are usually understood in the framework of non-asymmetric disk responses to density irregularities in a Keplerean disk that have a pitch angle of about 20°, and which has been confirmed by Cassini data for the case of the rings (Jeousek et al., Icarus 279:16-50, 2016). Unlike the stellar disk case however, the self-gravity wakes in the rings are satellite aggregates orbiting at the rate of their common center of mass. To study their motion we first model them as rigid bodies subject to different gravitational and concessional torques. With this simplistic model we manage to reproduce the observed pitch angle, and we can derive a relationship between the pitch angle and the shear rate of the disk which is consistent with numerical simulation of rings (Salo et al. Icarus 170:36-50, 2004) and of galactic spiral arms (Mishikoshi & Kokubo, ApJ 787:174, 2014). Finally, we introduce these wakes within a vertically perturbed disk with a propagating Bending Wave and find that their motion in this environment can lead to high velocity impacts that generate ejecta and an optical depth signal that depends on the slope of the wave. This ejecta can help to explain some surprising features seen in Bending Waves by the Cassini spacecraft.

Session: Resonant Dynamics and Consequences, Plus Disks!

Architectures of Compact Super-Earth Systems Shaped by Instabilities

Max Goldberg[1], Konstantin Batygin[1]
[1]California Institute of Technology, Pasadena, CA

Compact non-resonant systems of sub-Jovian planets are the most common outcome of the planet formation process. Despite exhibiting broad overall diversity, these planets also display dramatic

signatures of intra-system uniformity in their masses, radii, and orbital spacings. Although the details of their formation and early evolution are poorly known, sub-Jovian planets are expected to emerge from their natal nebulae as multi-resonant chains, owing to planet-disk interactions. Within the context of this scenario, the architectures of observed exoplanet systems can be broadly replicated if resonances are disrupted through post-nebular dynamical instabilities. Here, we generate an ad-hoc sample of resonant chains and use a suite of N-body simulations to show that instabilities can not only reproduce the observed period ratio distribution, but that the resulting collisions also modify the mass uniformity in a way that is consistent with the data. Furthermore, we demonstrate that primordial mass uniformity, motivated by the sample of resonant chains coupled with dynamical sculpting, naturally generates uniformity in orbital period spacing similar to what is observed. Finally, we find that almost all collisions lead to perfect mergers, but some form of post-instability damping is likely needed to fully account for the present-day dynamically cold architectures of sub-Jovian exoplanets.

Diversity of resonances in multi-planet resonant chains is a natural outcome of planet formation

Nader Haghighipour[1]
[1]Planetary Science Institute, Honolulu, HI

The discovery of multi-planet resonant chains such as those in TRAPPIST-1 and Kepler-90, where adjacent planets are in different resonances, has raised questions on the formation of these systems. It is widely accepted that these systems formed through the combination of migration and resonance-capture where migrating planets capture each other in resonances. There is, however, an issue with this scenario as migrating planets tend to capture each other in the same resonance. It has been suggested that tidal forces are the reason that resonant-chain planets are in different commensurabilities. The latter motivated us to examine the validity of this statement. We have carried out extensive simulations of planet formation and migration, and determined the probability of capture for different resonances. Results demonstrate that migrating planets can in fact be captured in different resonances confirming that the diversity of resonances observed in resonant chains is a natural consequence of the formation and resonance capture mechanism, and does not require a secondary process. Results also show that the probability of capture (and, therefore, the final commensurabilities) is highly depended on the characteristics of the systems, especially the planets' mass-ratio and migration speed. Finally, our simulations indicate that capture in a resonance never occurs at the resonance's exact commensurability and there is always some deviation. The extent of this deviation also depends on the mass-ratio and orbital characteristics of the planets and the mechanism through which migrating planets lose energy. This also confirms that unlike previous studies, no post-capture mechanism is needed to explain the deviation from exact resonances observed in Kepler (and RV) planet pairs. We present the details of our study and discuss their implications for the formation and orbital architecture of resonant, multi-planet systems.

Apsidal Architecture of Planetary Systems in Mean Motion Resonance

Jordan Laune[1], Laetitia Rodet[1], Dong Lai[1]
[1]Cornell University, Ithaca, NY

A protoplanetary disk (PPD) exchanges angular momentum with its young embedded planets through gravitational interactions, leading to planetary migration across the disk. Whenever two planets have periods near an integer ratio j:j+k, they can be captured into a mean motion resonance (MMR), which is characterized by the libration of a certain resonance angle. In this talk, we analyze first order (k=1), coplanar MMRs, which have resonance angles that are a linear combination of the two planets' mean longitudes and their longitudes of perihelion. A planet's MMRs migrate along with it, potentially sweeping up neighboring planets into resonance. The typical treatment of disk migration and resonance capture damps orbital eccentricities to zero. Post-capture, for first order resonances, the planet pair evolves into a configuration in which both planets' resonance angles librate and their longitudes of perihelia differ by 180 degrees ("apsidally anti-aligned"). Their eccentricities reach an equilibrium value which depends on the disk setup. This process has been well-studied in the literature. However, there are some observed systems which the standard treatment cannot explain. For example, the K2-19 system hosts two moderately eccentric planets close to, but just wide of, the 3:2 MMR which are apsidally aligned.

In this talk, we investigate how apsidal alignment can arise for two planets in resonance. To this end, we postulate theoretical eccentricity driving forces and add them to the standard migration model. We present numerical results for our model, which facilitates migration but drives the planets' eccentricites to a prescribed saturation value rather than zero. For some saturation eccentricities, we observe the planets to become apsidally aligned. In this configuration, both planets' original resonance angles cease to librate, but there is a combined resonance angle which still librates and traps the planets near the nominal resonance location. Conversely, we also find that eccentricity driving can destabilize the resonance, resulting in temporary capture for some of our systems. In others, capture can be disrupted entirely. These results imply that the K2-19 resonant pair could have interacted with an eccentricity driving force in the past.

Stability Constrained Characterization of the 23 Myr-old V1298 Tau System: Do Young Planets Form in Mean Motion Resonance Chains?

Roberto Tejada Arevalo[1], Daniel Tamayo[1], Miles Cranmer[1]
[1]Princeton University, Princeton, NJ

A leading theoretical expectation for the final stages of planet formation is that disk migration should naturally drive orbits into chains of mean motion resonances (MMRs). In order to explain the dearth of MMR chains observed at Gyr ages (<1%), this picture requires such configurations to destabilize and scramble period ratios following disk dispersal. Strikingly, the only two known stars with three or more planets younger than 100 Myrs, HR 8799 and V1298 Tau, have been suggested to be in such MMR chains, given the orbits' near-integer period ratios. We incorporate recent transit and radial velocity observations of the V1298 Tau system, and investigate constraints on the system's orbital architecture imposed by requiring dynamical stability on timescales much shorter than the system's age. We show that the recent radial-velocity mass measurement of V1298 Tau b places it within a factor of two of the instability limit, and this allows us to set significantly lower limits on the eccentricity (e_b ≤ 0.18 at 99.7% confidence). Additionally, we rule out a resonant chain configuration for V1298 Tau at > 99% confidence. Thus, if the~23 Myr-old V1298 Tau system formed as a resonant chain, it must have undergone an instability and rearrangement shortly after disk dispersal. We expect that similar stability constrained characterization of future young multi-planet systems will help inform planet formation models.

Three-Body Resonances in the Saturnian System

Maryame El Moutamid[1], Matija Cuk[2]
[1]Cornell University, Ithaca, NY, [2]SETI Institute, Mountain View, CA

Saturn has a dynamically rich satellite system, which includes at least three orbital resonances between three pairs of moons: Mimas-Tethys 4:2, Enceladus-Dione 2:1, and Titan-Hyperion 4:3 mean-motion resonances. Studies of the orbital history of Saturn's moons usually assume that their past dynamics was also dominated solely by two-body resonances. Using direct numerical integrations, we find that three-body resonances among Saturnian satellites were quite common in the past, and could result in a

relatively long-term, but finite capture time (10 Myr or longer). We find that these three-body resonances are invariably of the eccentricity type, and do not appear to affect the moons' inclinations. While some three-body resonances are located close to two-body resonances (but involve the orbital precession of the third body), others are isolated, with no two-body arguments being near resonance. We conclude that future studies of the system's past must take full account of three-body resonances, which have been overlooked in the past work.

Generating Stellar Obliquities in Systems with Broken Protoplanetary Disks

Marguerite Epstein-Martin[1,2], Juliette Becker[2], Konstantin Batygin[2]
[1]Columbia University, New York, NY, [2]Caltech, Pasadena, CA

Recent advances in sub-millimeter observations of young circumstellar nebulae have opened an unprecedented window into the structure of protoplanetary disks, which has revealed the surprising ubiquity of broken and misaligned disks. In this work, we demonstrate that such disks are capable of torquing the spin axis of their host star, representing a hitherto unexplored pathway by which stellar obliquities may be generated. The basis of this mechanism is a crossing of the stellar spin precession and inner disk regression frequencies, resulting in adiabatic excitation of the stellar obliquity. We derive analytical expressions for the characteristic frequencies of the inner disk and star as a function of the disk gap boundaries, and place an approximate limit on the disk architectures for which frequency crossing and resulting obliquity excitation are expected, thereby illustrating the efficacy of this model. Cumulatively, our results support the emerging consensus that significant spin-orbit misalignments are an expected outcome of planet formation.

Modeling the Irradiation Instability of Protoplanetary Disks

Michelle Vick[1], Yoram Lithwick[1]
[1]Northwestern University, Evanston, IL

In most parts of a protoplanetary disk, the temperature is controlled by stellar irradiation. Recent work suggests that these passively heated disks may actually be unstable (Watanabe & Lin 2008, Wu & Lithwick 2021, Ueda et. al 2021). In this presentation, I describe the nature of the ‘irradiation instability’ and present a 2D model to numerically explore the robustness of this instability in protoplanetary disks. The model accounts for thermal diffusion and non-hydrostaticity. Potential consequences of the irradiation instability include ALMA rings and gaps, and vortices and turbulence.

Session: Dynamics near supermassive black holes

Forming Young and Hypervelocity Stars in the Galactic Centre via Tidal Disruption of a Molecular Cloud

Aleksey Generozov[1], Sergei Nayakshin[2], Ann-Marie Madigan[3]
[1]Technion, Haifa, [2]University of Leicester, Leicester, [3]CU Boulder, Boulder, CO

The central parsec of our Galaxy contains young stars orbiting Sgr A*, a supermassive black hole. These include the isotropic S star cluster of B stars within ~0.04 pc of Sgr A*, as well as a larger disc containing O and Wolf--Rayet stars. I will discuss how the disc can form from the tidal disruption of a molecular cloud. Subsequent dynamical evolution can produce a secular gravitational instability in the disc that will

put some of its stars on nearly radial orbits. Sgr A* will tidally disrupt binaries on such orbits, producing S and hypervelocity stars.

Repeated tidal disruption events in supermassive black hole binaries

Denyz Melchor[1], Smadar Naoz[1], Brenna Mockler[2], Sanaea Rose[1], Enrico Ramirez-Ruiz[2]
[1]University of California, Los Angeles, Los Angeles, CA, [2]University of California, Santa Cruz, Santa Cruz, CA

Repeated Tidal Disruption Events (TDEs) have been recently reported as an intriguing phenomenon that takes place when a star on a bound orbit wanders too close to a supermassive black hole (SMBH). The star is only partially disrupted and it returns for a second encounter. Current observations suggest a few-years orbit for these stars. However, how do these stars migrate to such close distances without being completely disrupted? We propose a new mechanism that combines gravitational perturbations from a far-away SMBH companion with weak two-body interactions from the overall population of stars around the primary SMBH. We show that this new channel is not only efficient in yielding TDEs but it is also naturally producing repeated TDEs. Further, we demonstrate that the combination of those two is imperative to the formation of repeated TDEs.

Dynamical perturbations around an extreme mass ratio inspiral near resonance

Makana Silva[1], Christopher Hirata[2]
[1]The Ohio State University, Columbus, OH, [2]Ohio State University, Columbus, OH

Extreme mass ratio inspirals (EMRIs) - systems with a compact object orbiting a much more massive (e.g., galactic center) black hole - are of interest both as a new probe of the environments of galactic nuclei, and their waveforms are a precision test of the Kerr metric. This work focuses on the effects of an external perturbation due to a third body around an EMRI system. This perturbation will affect the orbit most significantly when the inner body crosses a resonance with the outer body, and result in a change of the conserved quantities (energy, angular momentum, and Carter constant) or equivalently of the actions, which results in a subsequent phase shift of the waveform that builds up over time. We present a general method for calculating the changes in action during a resonance crossing, valid for generic orbits in the Kerr spacetime. We show that these changes are related to the gravitational waveforms emitted by the two bodies (quantified by the amplitudes of the Weyl scalar ψ_4 at the horizon and at infinity) at the frequency corresponding to the resonance. This allows us to compute changes in the action variables for each body, without directly computing the explicit metric perturbations, and therefore we can carry out the computation by calling an existing black hole perturbation theory code. We plan to use this technique for future investigations of third-body effects in EMRIs and their potential impact on waveforms detected by LISA.

The Beginning of an END

Tatsuya Akiba[1], Ann-Marie Madigan[1]
[1]University of Colorado Boulder, Boulder, CO

The anisotropic emission of gravitational waves during the merger of two supermassive black holes can result in a recoil kick of the merged remnant. We show, via analytic and N-body work, that eccentric nuclear disks - stellar disks of eccentric, apse-aligned orbits - can directly form as a result. An initially circular disk of stars will align orthogonal to the black hole kick direction with a distinctive "check-mark" eccentricity distribution and a spiral pattern in mean anomaly. A tidal disruption event occurs when a star gets too close to the central supermassive black hole and gets ripped apart by the tidal gravity of the black hole. In an eccentric disk, the rate of tidal disruption events is significantly elevated compared to an isotropic configuration which could explain the high tidal disruption event rates observed in

post-starburst/merging galaxies. We discuss the evolution of eccentric nuclear disks and their corresponding tidal disruption event rates as a function of the gravitational recoil kick magnitude.

Session: Analysis of equilibrium collisionless systems: power and peril

Probing the Galactic Potential Using Optimal Transport Theory

Farnik Nikakhtar[1], Quentin Mérigot[2], Jason Hunt[3], Robyn Sanderson[1,3], Ravi K. Sheth[1], Roya Mohayaee[4], Bruno Lévy[5]
[1]University of Pennsylvania, Philadelphia, PA, [2]Université Paris-Saclay, Paris, [3]Flatiron Institute, New York, NY, [4]Institut d'Astrophysique de Paris, Paris, [5]Universités de Lorraine, Nancy

We present a novel approach based on optimal transport theory to determine the galactic potential from a single snapshot of the phase-space coordinates of stars in a Milky Way-type galaxy. We push forward the phase-space coordinates of stars with a set of trial potentials and then compute the Wasserstein distance between the input and the pushed-forward phase-space using a discrete-discrete optimal transport algorithm. Wasserstein distance is a powerful measure to define similarities between distribution functions in a non-parametric setting. Consequently, we find the potential that makes the phase-space distribution function stationary by using the Vlasov equation. Furthermore, this approach can be used to quantify the non-equilibrium characteristics of galactic systems. We show that our algorithm performs very successfully on a Plummer sphere model and discuss the prospects for applications to more realistic galaxy simulations and observational data from Gaia.

Orbital Torus Imaging on FIRE

Micah Oeur[1], Adrian Price-Whelan[2], Sarah Loebman[1], Andrew Wetzel[3], Robyn Sanderson[4], Arpit Arora[4]
[1]University of California, Merced, Merced, CA, [2]Flatiron Institute, New York, NY, [3]University of California-Davis, Davis, CA, [4]University of Pennsylvania, Philadelphia, PA

In this presentation, I will discuss Orbital Torus Imaging (OTI), a new dynamical inference method to measure the Milky Way's potential. OTI leverages gradients in stellar astrophysical quantities (like age and chemical abundances) as a function of dynamical quantities (like orbital actions or energy) - these quantities are newly available from large surveys like SDSS and Gaia. Initial analysis has yielded promising results; however, it is unknown how sensitive this technique is to the effects of disequilibria. It is therefore important to test this method on simulations wherein the potential is realistic and known. I will discuss my implementation of OTI for a 1-dimensional system with an isothermal distribution function embedded in a simple harmonic oscillator potential and successful recovery of the true potential parameter. I will also discuss testing OTI on several Feedback in Realistic Environments (FIRE) hydrodynamic simulations. Particularly, I will discuss my investigation of the impact of a merger event on the accuracy of this method to recover the true potential. Additionally, I will investigate how local overdensities from the star forming gas and feedback processes from spiral arms affect the results from this method. The FIRE cosmological simulations are an ideal testbed for OTI, as these simulated galaxies span a range of formation histories, allowing me to explore the limits on how well this method measures the dark matter potential. This research will inform our understanding of the bias of this novel method and allow us to improve the modeling to handle effects we find in simulations.

elocity dipoles in the halos of FIRE simulated galaxies

Alexander Riley[1]
[1]Texas A&M University, College Station, TX

One major source of disequilibrium in the Milky Way is its most massive satellite, the LMC. Kinematics of distant halo tracers show a velocity dipole in the Milky Way halo, which has been interpreted using N-body simulations as the LMC inducing a reflex motion in the Milky Way disk. In this talk, I discuss applying this framework to more realistic halos comprised of substructure from the FIRE-2 zoom-in cosmological simulations. Velocity dipoles are resolved in Milky Way-mass hosts experiencing an LMC-like interaction and evolve in a manner consistent with a two-body interaction between the stellar disk and the LMC analog. However, satellite galaxies and stellar streams can create velocity dipoles in systems that aren’t experiencing a major satellite accretion, suggesting that care must be taken to remove substructure in the Milky Way observations.

Dynamical modelling of satellite galaxies to infer galaxy-halo connection and cosmology

Kaustav Mitra[1], Frank van den Bosch[1]
[1]Yale University, New Haven, CT

Constraining the connection between galaxies and their host dark matter halos is essential to our understanding of galaxy formation and evolution. Galaxy-halo connection is highly sensitive to cosmological parameters, particularly Ω_m and σ_8. However, there is an ongoing tension between these cosmological parameters inferred by Planck from CMB, and those inferred by usual probes of galaxy-halo connection like galaxy clustering and weak lensing. This tension might hint at new physics beyond ΛCDM, but could also be a result of systematics not properly accounted for in galaxy clustering and lensing, such as halo assembly bias.

Satellite kinematics provides a novel way to infer galaxy-halo connection that is independent of halo assembly bias. We build on the work by van den Bosch et al. (2019), to improve ***Basilisk*** *(Bayesian hierarchical inference using satellite kinematics)* into a competitive probe of galaxy-halo connection, at par with, and complementary to, clustering and lensing. We perform forward modelling of projected separation and line-of-sight velocity of satellite galaxies using spherical Jeans equation. Testing our method on SDSS-like mock surveys produce precise and unbiased constraints on input galaxy-halo connection and cosmology.

Applying *Basilisk* on SDSS DR7, we obtain extremely tight constraints on the distribution of galaxies in dark matter halos, as well as satellite velocity anisotropy, over a very wide halo mass and galaxy luminosity range. Our results are consistent with previous studies that used various probes of galaxy-halo connection. But, due to our improved constraining power, we note interesting deviations from the standard galaxy-halo connection model used in the literature. Finally, we combine satellite kinematics with galaxy clustering to put constraints on cosmological parameters. Our preliminary results are consistent with Planck, and could indicate some unaccounted-for systematics in clustering+lensing studies.

Jeans modeling of Simulated Dwarf Satellites Around a Milky Way like Galaxy

Juan Guerra[1]
[1]Yale University, New Haven, CT

The dwarf spheroidal (dSph) satellite galaxies of the Milky Way provide a laboratory for studying the nature of dark matter. Using high resolution simulations of dwarf satellites around a Milky Way like Galaxy (The 'Mint' DC Justice League) we examine to what degree typical modeling assumptions bias derived properties such as the enclosed mass or overall shape of the density profile. We test the quantitative impact of these assumptions, including spherical symmetry and equilibrium, when made during Jeans modeling. Turning to the simulated systems, in which the effects of typically-ignored properties such as orbital position and history are included, we assess the robustness of Jeans modeling and the Wolf-mass estimator in these realistic contexts.

Posters

Chemically enriched Sun-like stars from engulfment of ultra-short-period planets

Christopher O'Connor[1], Dong Lai[1]
[1]Cornell University, Ithaca, NY

Spectroscopic studies of wide binary systems have revealed a substantial population where one star is enriched in refractory elements by up to ~0.1 dex relative to its companion. This has been tentatively attributed to the engulfment of a planet by the enriched star in each system. Chemical enrichment is observed in a large fraction (~30%) of systems, suggesting that planet engulfment is common. This is difficult to explain using standard models of dynamical evolution: simple hypotheses, such as planet-planet scattering in a ‘Kepler multi’ system or the Lidov-Kozai effect driven by an outer companion, fail to predict the observed prevalence of chemically enriched stars. We propose a scenario in which the engulfment originates from the tidal decay of a rocky ultra-short-period planet (USP). We construct a toy model of a population of planet-hosting Sun-like stars in which USPs form via gradual inward migration under external secular forcing, undergo rapid tidal decay at short orbital periods (<1 day), and enrich the stellar atmosphere when engulfed. Using that model, we show that one can simultaneously reproduce the observed fraction of stars with USPs (~1%) and the fraction with chemical enrichment at a typical age of a few Gyr. This implies constraints on both the average rate of USP formation per star and the average lifetime of an individual USP. We compare these constraints to predictions from existing models of USP migration and tidal evolution. In contrast with some previous studies, our results suggest that USPs can (and often do) undergo tidal decay during the main-sequence lifetimes of their host stars.

Diminished Generation of Stellar Obliquities: The Angular Momentum Budget During Resonance Crossing

Yubo Su[1], Dong Lai[1]
[1]Cornell University, Ithaca, NY

In the early stages of a planetary system, the host protostar's stellar spin axis is closely aligned with the angular momentum axis of its massive circumstellar disk. If the protostar also has a distant binary companion, then its spin axis can tilt substantially as the circumstellar disk depletes due to a secular resonance crossing. This process leaves the star with a substantial obliquity relative to its planet[s]. However, if the stellar angular momentum is non-negligible compared to the orbital angular momentum of its planet[s], this obliquity excitation process can be significantly diminished. We analyze the angular momentum budget during resonance crossing and show that the necessary conditions for efficient

obliquity generation can be analytically understood. We apply our results to show that the formation rate of hot Jupiters via high-eccentricity migration may be suppressed for certain parameters.

Debiasing the Minimum-Mass Extrasolar Nebula: Planet Multiplicity and the Diversity of Solid Density Profiles

Matthias He[1], Eric Ford[1]
[1]The Pennsylvania State University, State College, PA

A foundational idea in the theory of in situ planet formation is the "minimum mass extrasolar nebula" (MMEN), a power-law profile for the surface density of disk solids that is necessary to form the planets we see in their present locations. While the MMEN framework is intuitively simple, it continues to be debated whether most exoplanetary systems fit a universal disk template. Previous studies have relied on simplistic treatments for detection biases and the exoplanet mass-radius relationship to construct the MMEN from the Kepler planet catalog. The recent development of detailed forward models for the Kepler mission has enabled unprecedented inferences on the intrinsic population of inner planetary systems from the observed population, leading to advanced statistical models, such as the "maximum AMD model" that captures the underlying architectures and correlations in multi-planet systems. Here, we use simulated catalogs from this model to reconstruct the MMEN. Fitting a power-law relation for the solid surface density as a function of semi-major axis to each individual multi-planet system results in a diverse distribution of disk profiles. Our approach allows us to account for the role of non-transiting and undetected planets in altering the MMEN; we find that while transit observations do not tend to bias the inferred median power-law slope, they can lead to both over- and under-estimated normalizations for the disk density and thus significantly broaden the inferred distribution for MMEN mass. We use our model to explore how the MMEN varies with planet multiplicity and prescriptions for the feeding zone width, and discuss implications for planet formation.

Dancing Streams in Merging Halos: Effects of Major Mergers on Stellar Streams

Sachi Weerasooriya[1], Tjitske Starkenburg[2], Helmer Koppelman[3], Kathryn Jonston[4,5], Emily Cunningham[4]
[1]Texas Christian University, Fort Worth, TX, [2]Northwestern University, Evanston, IL, [3]Institute for Advanced Study, Princeton, NJ, [4]Flatiron Institute, New York, NY, [5]Columbia University, New York, NY

Stellar streams orbiting a galaxy are great probes of that galaxy's history. Streams exist of stars which together once formed a smaller system, a globular cluster or dwarf galaxy, that has been torn apart by tidal forces. Stellar streams may be used to constrain halo masses and detect dark-matter sub structures, or learn about smaller-mass systems and the formation history of the host galaxy. Previous studies have looked at the effects of the Large Magellanic Cloud (LMC) on stellar streams in the Milky Way. However, a complete sense of the impact of halo mergers on stellar streams remains unexplored. We run a suite of N-body simulations with streams around a Milky Way like halo during a major merger event with satellites with varying halo masses, and study the stream evolution during major and minor mergers. We characterize the differences in morphology, structure, and survival of streams during a galaxy interactions, and identify possible dependencies of their evolution on orbital properties, location, and ages. We find that streams can be significantly affected by mergers, and our results thus open up opportunities to study past mergers through stellar streams.

Hydrodynamical Evolution of Black-Hole Binaries Embedded in AGN Disks

Rixin Li[1], Dong Lai[1]
[1]Cornell University, Ithaca, NY

Stellar-mass binary black holes (BBHs) embedded in active galactic nucleus (AGN) disks are possible progenitors of black-hole mergers detected in gravitational waves by LIGO/VIRGO. To better understand the hydrodynamical evolution of BBHs interacting with the disk gas, we perform a suite of high-resolution 2D simulations of binaries in local disk (shearing-box) models, considering various binary mass ratios, eccentricities and background disk properties. We use the γ-law equation of state and adopt a robust post-processing treatment to evaluate the mass accretion rate, torque and energy transfer rate on the binary to determine its long-term orbital evolution. We find that circular comparable-mass binaries contract, with an orbital decay rate of a few times the mass doubling rate. Eccentric binaries always experience eccentricity damping. Prograde binaries with higher eccentricities or smaller mass ratios generally have slower orbital decay rates, with some extreme cases exhibiting orbital expansion. The averaged binary mass accretion rate depends on the physical size of the accretor. The accretion flows are highly variable, and the dominant variability frequency is the apparent binary orbital frequency (in the rotating frame around the central massive BH) for circular binaries but gradually shifts to the radial epicyclic frequency as the binary eccentricity increases. Our findings demonstrate that the dynamics of BBHs embedded in AGN disks is quite different from that of isolated binaries in their own circumbinary disks. Furthermore, our results suggest that the hardening timescales of the binaries are much shorter than their migration timescales in the disk, for all reasonable binary and disk parameters.

Local Group Dynamics with the Subaru Prime Focus Spectrograph

Carrie Filion[1], The PFS Galactic Archaeology Team[1]
[1]Johns Hopkins University, Baltimore, MD

The Subaru Prime Focus Spectrograph (PFS) will soon be embarking on an ambitious, multi-year survey that will investigate the nature of dark matter and the formation and evolution of structure on a variety of astrophysical scales. The planned observations include large numbers of faint stars in the Milky Way, in its satellite galaxies, and in M31. I will describe some of the exciting chemo-dynamical studies of the Local Group that these observations will enable, and I will discuss the insights that we hope to gain into the dynamical evolution of galaxies.

On the Correlation between Hot Jupiters and Stellar Clustering: High-eccentricity Migration Induced by Stellar Flybys

Laetitia Rodet[1], Yubo Su[1], Dong Lai[1]
[1]Cornell University, Ithaca, NY

Recent observational studies suggest that the occurrence of hot Jupiters (HJs) around solar-type stars is correlated with stellar clustering. We will present a new scenario for HJ formation, called “Flyby Induced High-e Migration”, that may help explain this correlation. In this scenario, stellar flybys excite the eccentricity and inclination of an outer companion (giant planet, brown dwarf, or low-mass star) at large distance (10–300 au), which then triggers high-e migration of an inner cold Jupiter (at a few astronomical units) through the combined effects of von Zeipel–Lidov–Kozai (ZLK) eccentricity oscillation and tidal dissipation. We will present the analytic estimate for the HJ occurrence rate in this formation scenario, that we obtained using semianalytical calculations of the effective ZLK inclination window, together with numerical simulations of stellar flybys. This “flyby induced high-e migration” could account for a significant fraction of the observed HJ population, although the result depends on several uncertain parameters, including the density and lifetime of birth stellar clusters, and the occurrence rate of the “cold Jupiter + outer companion” systems.

Environmental Effects on the Dynamical Evolution of Star Clusters in Turbulent Molecular Clouds

Paolo Suin[1], Steven Shore[1,2], **Vaclav Pavlik[3]**
[1]Dipartimento di Fisica, Universita di Pisa, Pisa, [2]INFN, Sezione di Pisa, Pisa, [3]Astronomy Department, Indiana University Bloomington, Bloomington, IN

Molecular clouds are usually ignored when modeling the structural and dynamical properties of the clusters that birth therein. The usual approach is to consider the feedback as a one-way process by which the stars erode the cloud. Yet despite this action, the cluster still finds itself imbedded in a dense, highly turbulent medium. Interactions with ambient gaseous structures modify its dynamical evolution from that expected if it were isolated. We studied young massive star clusters that remain within their initial cloud complex. Assuming the conditions of a translucent cloud whose mass is not substantially greater than the cluster, we simulated the cluster dynamical development by combining N-body and hydrodynamical codes within the Astronomical Multipurpose Software Environment (AMUSE). The clusters were modeled both with and without an initial mass function for the stars, and the evolution was followed with and without the ambient cloud medium for approximately 100 Myr. Most models reached core collapse and we examined the effects of the cloud on their subsequent evolution. The turbulent environment, even if not self-gravitating, produces a stochastic tidal acceleration that perturbs the cluster. Even without self-gravitation or stellar feedback, tidal harassment produces a lower density configuration more rapidly than the isolated reference simulations. The background is more effective on clusters in advanced stages of dynamical development. The asymptotic power-law density distribution exponent also shows substantially different evolution in the two cases, with the tidally disturbed systems displaying more extended, shallower halos. This study is based on Suin, P., 2022, MSc thesis, Physics, University of Pisa (https://etd.adm.unipi.it/t/etd-01062022-202945/).

Making Observational Predictions for the LMC’s Dynamical Friction Wake

Hayden Foote[1], Gurtina Besla[1], Nicolas Garavito-Camargo[2], Emily Cunningham[2], Lachlan Lancaster[3], Philip Mocz[4], Martin Sparre[5], Mark Vogelsberger[6]
[1]Steward Observatory, University of Arizona, Tucson, AZ, [2]Center for Computational Astrophysics, Flatiron Institute, New York, NY, [3]Department of Astrophysical Sciences, Princeton University, Princeton, NJ, [4]Lawrence Livermore National Laboratory, Livermore, CA, [5]Institut für Physik und Astronomie, Universität Potsdam, Potsdam, [6]Department of Physics, Massachusetts Institute of Technology, Cambridge, MA

As the Large Magellanic Cloud (LMC) makes its first infall to the Milky Way (MW), it is predicted to induce a trailing overdensity in the MW’s dark matter, known as a dynamical friction wake. Recently, the stellar counterpart of this wake, a trailing overdensity of stars, has been tentatively detected in the MW’s stellar halo (Conroy et al. 2021). Curiously, the observed stellar wake is denser than theoretically predicted in cold dark matter (CDM) simulations. To understand this discrepancy, it is crucial to determine the extent to which the CDM wake’s self-gravity contributes to the formation of the stellar wake in addition to the LMC’s gravity. We study the formation of the LMC’s CDM and stellar wakes using windtunnel-style *N*-body simulations, both with and without the CDM wake’s self-gravity. I will present results from this simulation suite, including new predictions for the observable kinematic signatures of the stellar counterpart to the CDM wake. I will also comment on implications for using observations of the LMC’s stellar wake as a probe of DM physics.

LSIM: a cloud-based tool for lunar mission analysis and design

Jorge A. Pérez-Hernández[1], Helge Eichhorn[1], Christian Laroque[1], Philippe Martin[1], Benjamin Boschmann[1], Riccardo Luise[1]
[1]Telespazio Germany GmbH, Darmstadt

During the last few years, there has been a renewed interest in Moon exploration. Lunar missions in the past have, in general, relied on existing Earth-based communication and navigation services [1]. The growing demand for these services, as well as its limited accuracy and coverage, calls for a dedicated lunar communications and navigation service [2]. Here, we present the Lunar Service Volume Simulator (LSIM), a cloud-based mission analysis and design software tool for lunar missions, and detail current capabilities of the simulator. LSIM has been partially funded through the ESA Lunar Communications and Navigation Service (LCNS) Phase A/B1 Study.

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Subhalos-stream interaction in the presence of massive satellites.

Arpit Arora[1], Nicolas Camargo[2], Robyn Sanderson[1,1]
[1]University of Pennsylvania, PHILADELPHIA, PA, [2]CCA, Flatiron, New York City, NY

Dark matter subhalos potentially can be detected when they interact with stellar streams, leaving perturbations along the stream track. Massive in-falling satellites such as the Large Magellanic Cloud (LMC) can create a dark matter wake that could lead to significant perturbations in the subhalo population of the host galaxy, complicating efforts to interpret possible interaction signatures. Using the FIRE-2 zoomed cosmological baryonic simulations, we explore the evolution of encounter rates between subhalos with masses 10^5-10^9 $M_{\odot}$ and a stellar stream orbiting at a distance of 20-40 kpc from the galactic center during a LMC-like merger. We use an analytic, axisymmetric treatment of flybys, assuming an isotropic Maxwellian distribution for the relative radial velocity and a uniform number density of subhalos at each time step, to estimate the number of encounters in this radial range as a function of sky position. While the LMC drags in a large number of subhalos at infall, most of them are quickly destroyed by tides; the survivors account for only about 10% of the total subhalo population after the first pericenter passage of the LMC analog. However, while the direct subhalo contribution does not substantially affect the global number density profile of subhalos, the merger significantly perturbs the global distribution of relative radial velocities for the subhalos, imparting a more circular nature to their orbits and improving the common assumption of a Maxwellian velocity distribution. Furthermore, the contributed subhalos are not uniformly distributed across the halo, but are concentrated near the pericenter of the interaction, where they can increase the encounter rate by up to a factor 5 as the LMC approaches pericenter.

Differential Apsidal Precession in Mean Motion Resonant Planetary Systems

Jordan Laune[1], Laetitia Rodet[1], Dong Lai[1]
[1]Cornell University, Ithaca, NY

In this poster, we consider first order, coplanar mean motion resonances (MMRs) between two planets orbiting a central primary. The corresponding resonance angles are a linear combination of the two planets' mean longitudes and their longitudes of perihelion. In real exoplanet systems, MMR planet pairs can be perturbed by various physical effects, such as secular precession from giant planetary companions or nodal precession due to an oblate star. For the case of a massive perturber on a circular orbit, differential apsidal precession between the two planets "splits" their resonant angles. To study this effect, we parametrize the effective differential precession rate and then investigate the effects of resonance splitting through time-dependent integrations of the interaction Hamiltonian. We begin with the test particle treatment of the problem and then present our results for comparable mass planets.

Janus: A NASA SIMPLEx mission to explore two NEO Binary Asteroids

Daniel Scheeres[1], Janus Science Team[1]
[1]University of Colorado Boulder, Boulder, CO

Janus is a NASA SIMPLEx mission currently in Phase C/D. Janus was selected in 2019 to be co-manifested with the NASA Discovery mission Psyche, and is scheduled to be launched in August 2022.

Janus will send two spacecraft, each of which will fly by a Near Earth Binary Asteroids in early 2026. The targeted binary asteroid systems are (175706) 1996 FG3 and (35107) 1991 VH. These asteroids have been observed using Earth-based optical, IR and radar telescopes for over two decades. These observations have provided precise global shape models and orbit information for each system, which in turn have exposed additional questions that require higher resolution observations to address.

(175706) 1996 FG3 Binary 1996 FG3 is a primitive C-Type asteroid. It has been documented to lie in a singly-synchronous state and was the first binary system to be documented to lie in a Binary YORP — Tide equilibrium Observation of the thermal properties of the secondary will allow us to gain insight into tidal dissipation occurring in the primary body, which will be an unprecedented measurement for a small rubble pile asteroid.

(35107) 1991 VH Binary 1991 VH is a rocky S-Type asteroid. It has a secondary that is not settled into the usually observed, minimum energy singly synchronous state. Instead, the secondary has been seen to exchange angular momentum and energy with the system orbit, leading to an apparent chaotic dynamical evolution. We will use our visible and thermal observations of the secondary and the entire system to better understand why this system is not in a lower-energy state, as most binaries are.

The overall Janus science goals are to understand the formation and evolutionary mechanics of binary rubble pile asteroids, and to understand the key features of each of the binary asteroid systems outlined above. The Janus science goals will be achieved by combining flyby observations of the target binary asteroids with ground-based observations of the systems. This combination will enable the high resolution imaging and thermal data to be placed into a global context, leveraging all available data to construct an accurate topographical and morphological model of these bodies. In addition, the dynamics of the binary asteroid systems will be fit across the encounter, from approach to departure observations, in order to constrain the mass and inertias of the system components, where possible.

Understanding the formation and evolution of binary asteroids provides a key to understanding the physical evolution and lifecycles of rubble pile asteroids. Janus will provide insight into these larger-scale evolutionary scenarios.

Probing Gaps in Globular Cluster Streams in External Galaxies with the Nancy Grace Roman Telescope

Christian Aganze[1], Sarah Pearson[2], Tjitske Starkenburg[3], Kathryn Johnston[4]

[1]University of California San Diego, San Diego, CA, NYU, New York, NY, Northwestern University, Evanston, IL, Columbia University, New York, NY

Cosmological simulations that include dark matter predict the existence of low-mass subhalos. These subhalos can perturb thin stellar streams formed by tidal disruption of globular clusters (GCs), creating a gap-like feature like those detected in Gaia data (e.g GD-1). While the gap morphology offers an avenue for constraining different dark matter models, the sample of GC streams in the Galaxy with confirmed gaps remains small due to the streams' intrinsic low surface brightness. Previously, Pearson et al. (2021) have shown that the Nancy Grace Roman Space Telescope (Roman) will detect thin streams in external galaxies originating from GCs with progenitor GC masses as low as 3 x 10^4 solar masses. It is unknown, however, if we can observe gaps in these streams in external galaxies. In this project, we generate mock streams and model subsequent subhalo interactions in thin streams orbiting in a Milky Way-like potential with initial GC masses of 3 x 10^4 solar masses and subhalo masses of 10^5-10^7 solar masses. We study the gaps created through the interaction between these subhalos and GC streams and predict detectability thresholds for these gaps by incorporating realistic background stars simulated in the Roman 0.28 deg^2 field of view projected to the distance of M31 and other nearby galaxies.