

# Abstracts of the 50th DDA Meeting (Boulder, CO)

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## 100 — Dynamics on Asteroids

### 100.01 — Simulations of a Synthetic Eurybates Collisional Family

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Of the six recognized collisional families in the Jovian Trojan swarms, the Eurybates family is the largest, with over 200 recognized members. Located around the Jovian L4 Lagrange point, librations of the members make this family an interesting study in orbital dynamics. The Jovian Trojans are thought to have been captured during an early period of instability in the Solar system. The parent body of the family, 3548 Eurybates is one of the targets for the LUCY spacecraft, and our work will provide a dynamical context for the mission. Recent modeling has suggested that some members of the family have escaped the swarm on a time scale comparable to the age of the Solar system. The aim of the present work is to provide a dynamical simulation of the early history of the Eurybates family to explain its origins. Our modeling involved the creation of a 1000 member synthetic fragment cloud, centered on 3548 Eurybates as the parent body. The synthetic family was created using the Gauss equations, with a 100m/s escape velocity and random ejection angles. The dynamical evolution of the synthetic cloud was modeled using high precision n-body simulations with the REBOUND code on a variety of time scales. From these simulations, we find that the synthetic family stabilizes into the modern observed libration pattern within a relatively short time span. By using statistical comparisons with the observed family members, our results provide the first estimate of the minimum age of the Eurybates family. The Eurybates collisional family also provides a unique opportunity to examine the dynamical evolution of the fragments of

break-up event around a Lagrange point.

### 100.02 — High-Fidelity Testing of Binary Asteroid Formation with Applications to 1999 KW4

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The commonly accepted formation process for asymmetric binary asteroids is the spin up and eventual fission of rubble pile asteroids as proposed by Walsh, Richardson and Michel (Walsh et al., Nature 2008) and Scheeres (Scheeres, Icarus 2007). In this theory a rubble pile asteroid is spun up by YORP until it reaches a critical spin rate and experiences a mass shedding event forming a close, low-eccentricity satellite. Further work by Jacobson and Scheeres used a planar, two-ellipsoid model to analyze the evolutionary pathways of such a formation event from the moment the bodies initially fission (Jacobson and Scheeres, Icarus 2011). They provide statistical analysis on the conditions for the bodies to enter a stable orbit, reimpact, escape, or fission further, forming a triple system. The planar, two-ellipsoid model used in this study ignores higher order mass parameters which have been shown to have significant influence on the dynamics of bodies in close proximity. To understand the effect of these terms, we apply recently developed high-fidelity, computationally efficient full two-body problem (F2BP) modelling tools, which allow us to represent each body as an arbitrary mass distribution in three-dimensional space. With this tool we perform a Monte Carlo analysis for the evolution of an asymmetric binary system from the point of fission until the system settles into a stable state or evolves further. During the dynamical simulations standard analytic methods for assessing asteroid breakup are used to assess the spin rate of the system; the simulation is halted in the case of fission, reimpact, or escape. We select 1999 KW4 as a test case because the shape, geometry, and dynamics of the system have been well characterized and provide the knowledge necessary for

such a high-fidelity analysis. At the end of this process we perform statistical analysis of the conditions for binary evolutionary pathway and contrast our results with those of Jacobson and Scheeres.

### 100.03 — The Dynamical Surface Environment of Tumbling Asteroids

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Non-principal axis rotating asteroids, or tumbling asteroids, are a small subset of known asteroids, observed both in the main asteroid belt and in near-Earth orbit. In non-principal axis rotation a body's angular velocity vector is not aligned with any of its principal axes, causing fluctuations in the evolution of the angular velocity direction and magnitude of the body. For tumbling asteroids such fluctuations lead to a dynamic environment on their surfaces. These dynamics manifest in an ever-changing geopotential, with surface accelerations and surface slopes changing magnitudes and directions. Research has shown that tumbling is not a stable state for an asteroid and that it tends to dissipate throughout the asteroid's lifetime. However, the existence of tumbling asteroids does point to some de-stabilizing mechanisms such as planetary flybys and the Yarkovsky–O'Keefe–Radzievskii–Paddack effect. The former being an immediate impulsive mechanism and the latter perturbing an asteroid's rotation over millennia. We investigate the surface environment of several asteroids, both observed and hypothetical, combining their angular velocity vectors and the shape models to examine the fluctuations in surface accelerations and surface slopes. In addition, we examine motion trends on the surfaces of such bodies, seeking to understand what would happen to particles placed on the surface as the asteroid tumbles and as the tumbling state suddenly changes. The sudden change in tumbling state of asteroid (99942) Apophis is examined in particular due to its expected flyby of Earth in 2029 and possibility of mass shedding after to the encounter.

### 100.04 — Disassociation Energies for Rubble Pile Asteroids

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We study the disassociation of rubble pile asteroids under rapid spin rates and the resultant asteroid pairs and clusters that can arise as a function of

the system angular momentum and energy. To do this rigorous results from Celestial Mechanics are applied to determine the Hill Stability of a rubble pile asteroid spun fast enough to disassociate into its component pieces. Depending on the overall energy and angular momentum in the system, the number of components that can escape will be limited. If the rubble pile consists of N components, the energy required for different combinations of components to escape can be related to the integer partitions of the number N. If the rubble pile is modeled as a size distribution with a given porosity, the energy required to disrupt the system into different clusters can be reduced to a power series summation. This talk reviews the application of Hill Stability theory to this problem and presents the overall conclusions and their implications for forming asteroid pairs and clusters.

### 100.05 — The Dynamics of Surface Launched Particles around Bennu

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The OSIRIS-REx spacecraft has recently discovered small particles being ejected from the surface of the near-Earth asteroid Bennu. Observations to date have shown that a number of particles have survived in orbit for multiple days after leaving the asteroid surface, while others escape or quickly return to the surface. This behavior is governed by the complex dynamical environment near the surface of small asteroids, as well as the constraints on the launching conditions provided by the spacecraft observations. This talk will explore the effects of the different forces that influence these trajectories, and will demonstrate the surprising variety of orbits that can be produced in this environment.

### 100.06 — Earth's missing Trojans: Lessons from Mars and the role of radiation forces

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There is renewed interest in the possibility of stable Trojan asteroids of the Earth and observational constraints from the recent search by the OSIRIS-REx spacecraft allow a population of at least several tens of few-hundred-m-sized such asteroids (Cambioni et al, 2018). These objects may represent leftover material from the formation and early evolution of the terrestrial planets (Malhotra, 2019).

If primordial terrestrial Trojans do exist, the closest analogue population within our solar system is probably the small retinue of Trojans hosted by Mars at moderate (15-30 deg) inclination, compared to the <10 deg inclination region where long-lived Earth Trojans should exist. Though limited in number, the population of Mars Trojans hints at an intriguing evolutionary history. Their orbits are strongly clustered, indicating a genetic association to one of the largest Trojans, (5261) Eureka. The bulk physical properties and orbit distribution of these asteroids as well as the existence of relatively large but orbitally isolated Trojans, is most readily explained by the long-term action of solar-radiation-driven forces operating at 1.5 au from the Sun. In this scenario, YORP is primarily responsible for creating new asteroids while Yarkovsky determines their orbit distribution, stability and rate of escape from the Trojan clouds (Cuk et al, 2015; Christou et al, 2019). Interestingly, Trojan longevity depends as much in the direction of the Yarkovsky acceleration as in the magnitude.

To better understand how the example of Mars might apply to an extant population of Earth Trojans, I carry out test particle simulations over timescales of a few Gyr, relevant to Yarkovsky-driven evolution. In the process, I confirm and extend the earlier result by Cuk et al (2012) that horseshoe orbits are as likely to survive as tadpoles under planetary perturbations. In this presentation I will show how the inclusion of Yarkovsky affects the residence time of Earth trojan and horseshoe asteroids compared to point-mass forces alone. I will then discuss whether an old population of Earth coorbitals can be accommodated under the new dynamical constraints and how they might affect the NEA population in the vicinity of Earth's orbit.

#### **100.07 — Radar Astrometry of Near-Earth Asteroids from the Arecibo Observatory: 2018-2019**

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Arecibo Observatory has the world's most powerful planetary radar system, which provides ground-based observations whose quality could only be exceeded with a spacecraft flyby. It allows one to characterize near-Earth objects (NEOs) in terms of size, shape, spin, and surface properties, and to discover natural satellites that form binary and triple asteroid systems. In addition, radar astrometry is a valuable tool for orbit refinement, providing precise measurements that can significantly improve the accuracy of orbit determination.

We present an overview of radar astrometric observations obtained using the Arecibo planetary radar system since January 2018. Especially for newly discovered objects, that usually have large orbit uncertainties, Doppler and/or range measurements can prevent the object from being lost and requiring re-discovery in the future. We'll present a list of targets that had their orbits secured after radar observations, and an evaluation of how much radar helped to reduce their orbital uncertainties.

Every year about 40-60 recently discovered NEOs are observed at Arecibo. From January 1, 2018 to March 31, 2019, 90 NEOs were observed at Arecibo, including a comet. A total of 44 were newly discovered objects, almost half of the observed targets, and 33 are designated as potentially hazardous asteroids (PHAs). At least one Doppler measurement was obtained for each target, plus at least one range measurement for 55 of them.

Radar offers the great advantage of controlling the properties of the transmitted signal. The changes in the received echo compared to the transmitted signal provides clues about the characteristics of the object. The time delay gives information about the distance to a target with precision as fine as meters, and the Doppler-shifted frequency of the echo provides the radial velocity with precision as fine as mm/s, making it possible to detect even small changes in the orbit due to perturbations, such as the nongravitational acceleration generated by the Yarkovsky effect. Radar astrometry can also quickly eliminate impact false alarms with the improvement of estimates of an asteroid's orbital elements. Therefore, radar astrometry is crucial for planetary defense.

## 100.08 — On the Anomalous Acceleration of 1I/2017 U1 ‘Oumuamua

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We show that the  $P \sim 8$  h photometric period and the astrometrically measured  $A_{\text{ng}} \sim 2.5 \times 10^{-4}$  cm s<sup>-2</sup> non-gravitational acceleration (at  $r \sim 1.4$  AU) of the interstellar object 1I/2017 (‘Oumuamua) can be explained by a nozzle-like venting of volatiles whose activity migrated to track the sub-solar location on the object’s surface. Adopting the assumption that ‘Oumuamua was an elongated  $a \times b \times c$  ellipsoid, this model produces a pendulum-like rotation of the body and implies a long semi-axis  $a \sim 5 A_{\text{ng}} P^2 / 4\pi^2 \sim 260$  m. This scale agrees with the independent estimates of ‘Oumuamua’s size that stem from its measured brightness, assuming an albedo of  $p \sim 0.1$ , appropriate to ices that have undergone long-duration exposure to the interstellar cosmic ray flux. Using ray-tracing, we generate light curves for ellipsoidal bodies that are subject to both physically consistent sub-solar torques and to the time-varying geometry of the Sun-Earth-‘Oumuamua configuration. Our synthetic light curves display variations from chaotic tumbling and changing cross-sectional illumination that are consistent with the observations, while avoiding significant secular changes in the photometric periodicity. If our model is correct, ‘Oumuamua experienced mass loss that wasted  $\sim 10\%$  of its total mass during the  $\sim 100$  d span of its encounter with the inner Solar System and had an icy composition with a very low  $[C/O] \lesssim 0.003$ . Our interpretation of ‘Oumuamua’s behavior is consistent with the hypothesis that it was ejected from either the outer regions of a planetesimal disk after an encounter with an embedded  $M_p \sim M_{\text{Nep}}$  planet or from an exo-Oort cloud.

## 101 — Formation, Dynamical Evolution, and Detection of Circumbinary Planets

### 101.01 — Circumbinary disks: Planet formation in a dynamically complex environment

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Circumbinary disks around young stars have been observed to be misaligned to the binary orbital plane. A misaligned circumbinary disk evolves towards one of two states: alignment with the binary orbital plane or polar alignment where the disk is approximately perpendicular to the binary orbital plane. With analytic and numerical methods we explore how the binary and the disk properties affect the process. The disk evolution has important implications for planet formation around binary star systems.

### 101.02 — Multi-planet disc interactions in binary systems

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Understanding the evolution of multi-planet systems in binary stars is crucial to explaining observed exoplanet orbital properties. In particular, most massive extrasolar planets have significantly eccentric orbits and misalignments of planets very close to their host star are quite common. We examine the evolution of a misaligned multi-planet-disc system around one component of a binary star. We find that planets that open gaps in a tilted disk become misaligned with respect to the disc and to each other. In addition, the planet orbits can become eccentric due to the Kozai-Lidov effect. We find also that the innermost planet inclination can reach very high values and its motion can switch from prograde to retrograde.

### 101.03 — Using orbital dynamics to detect circumbinary planets: A novel approach

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One of Kepler’s most exciting breakthroughs was the discovery of circumbinary planets. Only about a dozen were found, however, leaving a vast gap in our understanding — similar to the state of exoplanet science when only hot Jupiters were known. TESS, and

only TESS, will allow us to detect an order of magnitude more circumbinary planets using a novel technique we have developed and tested: the occurrence of multiple transits during one conjunction. In addition to enchanting individual-case discoveries and their intriguing dynamics, our sample will enable statistical studies of occurrence rates, formation, and habitability.

#### 101.04 — Planet migration in circumbinary disks and the boundary of stability

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It is widely accepted that circumbinary planets form at large distances from their host binaries and undergo (substantial) radial migration. It is also well understood that in a circumbinary disk, planets stop migration at the edge of the disk cavity due to the tidal effect of the binary on the gaseous disk. It has been argued that the latter also corresponds to the boundary of orbital stability, promoting the idea that circumbinary planets stop migration at the edge of the stability region. To examine this idea, we have initiated a large program on understanding planet migration in circumbinary disk, focusing specifically on the stopping locations of planet in term of the disk's physical properties. We considered the central binary to be Kepler 38 and planet to be 10 and 15 Earth-masses, and carried out a large number of planet migration simulations for different values of the viscosity and scale height of the disk. In order for simulations to be self-consistent, we allowed the planet interact with the disk and migrate as the disk evolves. As expected, in the majority of cases, planet migrated inward and stopped at the same location on the edge of the cavity. This is consistent with the fact that planet migration is independent of the dynamical history of the system and is solely driven by the physical properties of the gas. Our simulations did not indicate any logical and causal connection between the stopping location of the planet and the boundary of orbital stability around the binary. We will present the results of our simulations and discuss their implications in more detail.

## 102 — Dynamics of Satellites

### 102.01 — The Gravity Field of the Saturnian System and the Orbits of Saturn's Satellites

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Since the end of the *Cassini* mission we have been working on a comprehensive reconstruction of the path of the *Cassini* spacecraft from the time of its insertion into orbit about Saturn to the time of its plunge into Saturn's atmosphere. The reconstruction relies upon a common set of planet and satellite ephemerides and gravity parameters. The data set used to determine the *Cassini* trajectory, the Saturn orbit, the satellite orbits, and the gravity field contains: *Cassini* Doppler tracking, radiometric range, optical navigation and Imaging Science observations, and very-long baseline interferometric (VLBI) observations; *Pioneer 11* Doppler tracking; *Voyager* Doppler tracking, radiometric range, and optical navigation observations; Earth-based and *Hubble Space Telescope* satellite astrometry; satellite mutual events (occultations and eclipses); Earth-based planet and satellite transits; Saturn ring stellar occultations observed from the Earth, with the *Voyager 2* Photopolarimeter (PPS), and the *Cassini* Visual and Infrared Mapping Spectrometer (VIMS) and Ultraviolet Imaging Spectrograph (UVIS); Saturn ring occultations measured with the *Voyager 1* and *Cassini* Radio Science Subsystem (RSS).

In this paper we discuss our findings concerning the masses of the satellites, Saturn, and Saturn's rings, and the gravity fields of Enceladus, Dione, Rhea, Titan, and Saturn. We compare our results with those published by the *Cassini* Gravity Science Team. We also summarize our results concerning the satellite orbits.

### 102.02 — And Then There Was One

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Titan, Saturn's lonely giant, is an anomaly, as described by Rimlinger & Hamilton at the 2018 DDA meeting. Then, we argued that Titan could have formed after an initially stable resonant chain of satellites underwent dynamical instability. For simplicity, we simulated a worst-case scenario with powerful eccentricity damping forces. We found that three-body resonances could be disrupted, but orbits did not cross and the bodies did not merge due to the

stabilizing effects of the damping forces. Now, we simulate three satellites orbiting Saturn for 160 Myr using twenty five unique mass configurations with more realistic eccentricity damping assumptions to explore instabilities that lead to mergers. We initialize the bodies in the 1:2:4 mean motion resonance and simulate tidal migration of the innermost body only. We augment the migration rate by a factor of  $\sim 10$ -100, but it remains well within the adiabatic limit for the resonances of interest. In one of our scenarios, we damp only the inner body's eccentricity. We observe instabilities in seven cases, all of which occur when the outer body is more massive than one or both of the inner two; this feature may be a necessary (but insufficient, as per, e.g., the Galilean moons) condition for instability. In most cases, instabilities happen when the radial center of mass  $q$  of the moons lies well beyond Titan's current semimajor axis ( $\sim 21 R_S$ ). However, in one case, the system goes unstable quite early, when  $q = 19.4 R_S$ . This simulation is promising because it not only verifies that dynamical instabilities are possible but also suggests that they can yield Titan analogues. We are now exploring more realistic eccentricity damping rates that scale like  $m_s r^{-6}$ , where  $m_s$  is the mass of the satellite and  $r$  is the distance from Saturn. Although eccentricity damping tends to stabilize systems, our additional damping terms will in general be small, so they may not cause dramatic differences in our results. We will report on our findings, emphasizing any divergence from our earlier results along with any additional instabilities, especially those that go unstable with  $q \sim 21 R_S$ .

### 102.03 — Evolution of Saturn's mid-sized moons

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The orbits of Saturn's inner mid-sized moons (Mimas, Enceladus, Tethys, Dione and Rhea) have been notably difficult to reconcile with their geology. Here we present recently published numerical simulations (Neveu & Rhoden 2019) coupling thermal, geophysical and simplified orbital evolution for 4.5 billion years that reproduce the observed characteristics of their orbits and interiors, provided that the outer four moons are old. Tidal dissipation within Saturn expands the moons' orbits over time. Dissipation within the moons decreases their eccentricities, which are episodically increased by moon-moon interactions, causing past or present oceans to exist

in the interiors of Enceladus, Dione and Tethys. In contrast, Mimas's proximity to Saturn's rings generates interactions that cause such rapid orbital expansion that Mimas must have formed only 0.1–1 billion years ago if it postdates (or forms together with) the rings. The resulting lack of radionuclides keeps it geologically inactive. These simulations explain the Mimas–Enceladus dichotomy, reconcile the moons' orbital properties and geological diversity, and self-consistently produce a recent ocean on Enceladus. These results are sensitive to unknown initial conditions, such as the initial orbits and time of formation of the moons. They cover a small fraction of an immense parameter space, especially regarding the time and frequency dependence of tidal dissipation inside Saturn, the rings' mass through time, and the number of moons through time (a balance between accretion/capture and collisions/ejections). The simplifications in the orbital modeling remain to be checked with N-body simulations. Despite these limitations, coupled modeling of interior and orbital evolution holds the key to unlocking questions such as the age of Enceladus' ocean, the properties of Saturn's interior, and the age of its rings.

Reference: Neveu, M. and Rhoden, A.R. (2019) Evolution of Saturn's mid-sized moons. *Nature Astronomy*, doi: 10.1038/s41550-019-0726-y

The code used to carry out these simulations is freely available at <https://github.com/MarcNeveu/IcyDwarf>.

### 102.04 — The Orbital Connection between Mimas and Enceladus

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The observed internal heating of Saturn's moon Enceladus is driven by its 2:1 Mean Motion Resonance (MMR) with the moon Dione that excites Enceladus' eccentricity. In light of the measurements of a high dissipation rate of Saturn (Lainey et al., 2012, 2017), it is likely that this resonance is currently in (or near) an equilibrium. However, an explanation is still needed for the fact that Enceladus is currently in the e-Enceladus sub-resonance of the 2:1 MMR, as other sub-resonances should have been encountered earlier, and would have had a very high probability of resonant capture. In this work, we attempt to explain the capture into the current Enceladus-Dione 2:1 MMR via the hypothesis of a "handoff" scenario between the Mimas-Enceladus 3:2 MMR and the Mimas-Dione 3:1 MMR. We find that Mimas

would affect the Enceladus-Dione MMR by i) creating orbital overlap of resonances, during which the eccentricity of Mimas is excited to its current value, ii) pushing Enceladus outward faster and thus contributing to its capture into the present MMR. Our model can explain the time scale of less than 100 Myr for capture of Enceladus into MMR with Dione, despite their slow orbital convergence.

### 102.05 — Dynamical History of the Uranian Satellites

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The five Uranian major satellites are not currently in any mean motion resonance. Large orbital inclination of Miranda, and geological evidence of past tidal heating of Miranda and Ariel both suggest that the system did experience dynamical excitation in the past, likely due to mutual resonances. In the literature the favored mechanism for exciting Miranda's inclination is the past 3:1 mean-motion resonance (MMR) between Miranda and Umbriel (Titemore and Wisdom, 1989; Malhotra and Dermott, 1990). However, much of the work on Uranian satellite dynamics has been done semi-analytically using averaged Hamiltonians, with only specific resonant terms taken into account. Here we use a symplectic integrator to revisit the last likely resonance between Uranus's major moons, the 5:3 Ariel-Umbriel MMR, previously studied by Titemore and Wisdom (1988). We find that this resonance tends to be highly chaotic as its sub-resonances are not separated. Therefore, the Ariel-Umbriel 5:3 MMR should excite both eccentricities and inclinations of Ariel and Umbriel. Furthermore, we find that Ariel-Miranda secular coupling communicates the resonant effects to Miranda, exciting Miranda's eccentricity and inclination. Current low inclinations of Ariel and Umbriel imply a period of string tidal damping (probably by Ariel) while these moons were still in the resonance. Breaking of the resonance is easy in the absence of such tidal dissipation within Ariel, but appears to be much harder if Ariel is dissipative and keeps the moons' eccentricities low. We are currently exploring whether interactions with Miranda could break the Ariel-Umbriel resonance and help reproduce the current system, and we will present the results at the meeting.

### 102.06 — Orbits and resonances of the regular moons of Neptune

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The Neptune system consists of seven regular inner moons, Triton, Nereid, and five irregular outer moons. Naiad, Thalassa, Despina, Larissa, Galatea, and Proteus are the regular moons discovered by the Voyager 2 spacecraft during the 1989 flyby of Neptune. The seventh regular moon – Hippocamp was discovered in 2013 by the Hubble Space Telescope (HST). We report integrated orbital fits for these moons based on the most complete astrometric data set to date, with position measurements from Earth-based telescopes, Voyager 2, and the HST observations covering 1981-2016. Our orbital model accounts for the equatorial bulge of Neptune, perturbations from the Sun and the planets, and perturbations from Triton. We summarize the fits in terms of state vectors, mean orbital elements, and plane-of-sky uncertainties. The orbital uncertainties show that the positions of the satellites are known within several hundred kilometers until at least 2030. We found that the inner-most moons, Naiad and Thalassa, are in 73:69 mean motion resonance that also involves the node of Naiad. This fourth-order resonance is unique among the planetary satellites. We estimated GMs of Naiad and Thalassa of  $GM_{Naiad} = 0.0080 \pm 0.0043 \text{ km}^3 \text{ s}^{-2}$  and  $GM_{Thalassa} = 0.0236 \pm 0.0064 \text{ km}^3 \text{ s}^{-2}$ . More high precision astrometry is needed to better constrain their masses. We also found that the newly discovered Hippocamp is in a 13:11 near-resonance with Proteus and the future astrometry of Hippocamp could reveal the mass of Proteus. The GMs of Despina, Galatea, and Larissa are more difficult to measure because they are not in any direct resonances and their masses are small.

## 103 — Dirk Brouwer Award Lecture

### 103.01 — Numerical Methods for Astrophysical Fluid Dynamics

*James Stone<sup>1</sup>*

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I will discuss recent advances in the development of numerical methods for astrophysical fluid dynamics, especially magnetohydrodynamics (MHD). A variety of different methods are now in common use, including structured mesh codes with adaptive mesh refinement, moving-mesh methods, and particle-based discretizations. Some comparisons between these methods on astrophysical problems of interest, such as MHD instabilities and turbulence, will be described. Extensions of these methods to more complex physics, such as radiative transfer, chemical and nuclear reaction networks, and general relativity will be presented. Results from application of these methods to study problems in accretion physics, turbulence and star formation in the interstellar medium, and planet formation will be discussed. The continuing rapid advance in performance of modern computer systems (with exascale systems planned in the next 2 years) will only increase the range of future discoveries enabled by computational fluid dynamics in astrophysics.

## 104 — Vera Rubin Prize Lecture

### 104.01 — The LMC vs. the Milky Way

*Gurtina Besla*<sup>1</sup>

<sup>1</sup> *Astronomy, University of Arizona (Tucson, Arizona, United States)*

Recent advancements in astrometry and in cosmological models of dark matter halo growth have significantly changed our understanding of the dynamics of the Local Group. The most dramatic changes owe to a new picture of the structure and dynamics of the Milky Way's most massive satellite galaxy, the Large Magellanic Cloud (LMC), which is most likely on its first passage about the Milky Way and ten times larger in mass than previously assumed. I will discuss the implications of the LMC's passage on the dynamics of the Milky Way and its satellites and provide a look forward to the era of high precision astrometry in the Andromeda system.

## 200 — In Honor of the Contributions of Andrea Milani

### 200.01 — The Dynamical Evolution of Asteroid Families

*William Bottke*<sup>1</sup>; *David Vokrouhlicky*<sup>2</sup>

<sup>1</sup> *Southwest Research Institute (Boulder, Colorado, United States)*

<sup>2</sup> *Charles University (Prague, Czechia)*

One of Andrea Milani's great interests involved the origin, evolution, and age of asteroid families. In my talk, we will discuss recent advances in this topic, how well our current family evolution models compare to observations/constraints, how certain families may be linked to asteroids observed by spacecraft, and the prospects for specific families to produce asteroid showers.

A key example in this talk will be the Flora family. It was formed from the catastrophic disruption of a diameter  $D > 150$  km parent body, and it dominates the innermost main belt region. Flora family members, when pushed onto planet-crossing orbits, also have relatively high probabilities of striking the Earth, Moon, and Mars. To quantify what happened, we used collisional and dynamical models to track the evolution of Flora family members immediate after the family-forming event. We created an initial Flora family and followed test asteroids using a numerical code that accounted for planetary perturbations and non-gravitational effects (e.g., Yarkovsky and YORP thermal forces). We found that our test Flora family members can reproduce the observed semimajor axis, eccentricity, and inclination distributions of the real family after  $1.4 \pm 0.3$  Ga. This age not only reproduces the crater retention age of Flora-family member (951) Gaspra, but also sample ages returned by Hayabusa from Itokawa, a likely escaped Flora family member. Additional work shows that an "asteroid shower" by Flora family members was a major source of impactors to both the mid-Proterozoic Earth and Amazonian-era Mars, with potentially interesting implications for each world in terms of the evolution of their biospheres.

We have also done comparable work on the Eulalia and New Polana families, likely sources for sample return targets Bennu and Ryugu. Intriguingly, like Itokawa, the largest craters on these small worlds yield crater retention ages consistent with the estimated dynamical ages of the source families. Collectively, these results imply that many small bodies are less susceptible to resurfacing processes via YORP spin-up mechanisms than previous thought, with "stochastic YORP" a possible means to have many asteroids avoid mass shedding events.

### 200.02 — New advances on chaotic orbit determination

*Federica Spoto*<sup>1</sup>; *Daniele Serra*<sup>2</sup>

<sup>1</sup> *Observatoire de la Côte d'Azur (Nice, France)*

<sup>2</sup> *University of Pisa (Pisa, Italy)*

Chaotic orbit determination intervenes in many practical problems, such as the chaotic rotation state of a celestial body, the chaotic orbit of a planet-crossing asteroid experiencing many close approaches, or the chaotic orbit of a spacecraft orbiting a giant planet system undergoing many close encounters with its satellites. Chaotic dynamical systems are characterized by the existence of a predictability horizon, connected to its Lyapounov time, beyond which the prediction of the state starting from the initial state of the system loses its meaning. Spoto and Milani (2016) apply the differential corrections algorithm for the determination of an orbit and of a dynamical parameter of a simple discrete system, the standard map. They define a computability horizon, a time limit beyond which numerical calculations are affected by numerical instability, and gives a formula for approximating its value.

We test, in the same case of the standard map, the constrained multi-arc method with the goal of pushing forward the computability horizon inherent in the least squares orbit determination (Serra, Spoto and Milani 2018). This method entails the determination of an orbit of a dynamical system when observations are grouped in separate observed arcs. For each arc a set of initial conditions is determined and during the orbit determination process all subsequent arcs are constrained to belong to the same trajectory. We show that the use of these techniques in place of the standard least-squares method has significant advantages: not only can we perform accurate numerical calculations well beyond the computability horizon, in particular, the constrained multi-arc strategy improves considerably the determination of the dynamical parameter.

### 200.03 — Planetary close encounters: an analytical approach

*Giovanni Valsecchi*<sup>1,2</sup>

<sup>1</sup> IAPS-INAF (Roma, Italy)

<sup>2</sup> IFAC-CNR (Sesto Fiorentino, Italy)

Close encounters with the planets play an important role in the dynamical evolution of objects in planet-crossing orbits. This subject has been most often dealt with using massive numerical integrations; however, some useful insight can be obtained using an analytic approach, at the price of having to treat the problem in a simplified version of the restricted 3-body problem. This presentation addresses some issues related to the motion of strongly scattered small bodies in the outer planetary region.

### 200.04 — The tale of three small impacting asteroids

*Davide Farnocchia*<sup>1</sup>; *Steven R. Chesley*<sup>1</sup>; *Paul W. Chodas*<sup>1</sup>; *Eric Christensen*<sup>2</sup>; *Richard A. Kowalski*<sup>2</sup>; *Peter G. Brown*<sup>3</sup>; *Peter Jenniskens*<sup>4</sup>

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The asteroid community has been engaged in the effort of characterizing and mitigating the near-Earth object impact hazard for over two decades. The priority was initially on objects larger than a kilometer that could cause global devastation, and this focus was later extended to objects larger than 140 m that could cause substantial regional damage if they reached the Earth, which happens with a mean interval of approximately 10,000 years. On the other hand, smaller objects reach the Earth more frequently. In particular, objects of several meters in size reach the Earth every few years and since 2008 three of them were indeed discovered by the Catalina Sky Survey within a day prior to impact: 2008 TC3, 2014 AA, and 2018 LA. Though these three asteroids caused no damage, they represented good test cases for how the near-Earth object tracking and hazard assessment systems can cope with short-term impactors. We discuss the processes of discovery, tracking, orbit characterization, and impact location estimation for these three objects, outlining commonalities and differences between them. While 2014 AA impacted above the Atlantic Ocean, fragments of 2008 TC3 and 2018 LA landed in Sudan and Botswana, respectively. Our impact location estimates allowed the recovery of the corresponding meteorites.

### 200.05 — Orbit determination for space missions in Pisa: results and simulations from Juno and BepiColombo

*Daniele Serra*<sup>1</sup>; *Giacomo Lari*<sup>1</sup>; *Giulia Schettino*<sup>2,1</sup>; *Giacomo Tommei*<sup>1</sup>

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<sup>2</sup> IFAC-CNR (Sesto Fiorentino, Florence, Italy)

The gravitational field of a planet is the main source of information about its interior structure, providing, e.g., constraints on the core size or the state of rotation. The most effective way to map a planet's gravity is by means of an orbiter which is endowed with a radio communication system. The radio link

allows measurements of the spacecraft’s range and range-rate, which can be used to reconstruct its orbit and ultimately to determine a number of physical parameters relative to the planet, including the coefficients of its gravitational field’s spherical harmonic expansion. The same data can be used to undertake fundamental physics experiments, like the determination of the parameters relative to the Parametrized Post-Newtonian formulation of the metric theories of gravity. The aim of this presentation is to summarize the main results about the Radio Science Experiments of the NASA’s Juno mission, now orbiting Jupiter, and the ESA/JAXA’s BepiColombo mission, launched in October 2018 to reach Mercury in 2025, obtained at the University of Pisa using the self-developed ORBIT14 orbit determination code. As regards the Juno mission, we show a solution of Jupiter’s gravity field obtained by analysis of real data from the first two Juno gravity orbits, and compare it to the one obtained with the JPL’s operative software MONTE ([1]). As far as the BepiColombo mission is concerned, we present numerical simulations of the Superior Conjunction Experiment for the determination of the PPN parameter  $\gamma$ , related to the space-time curvature.

[1] Iess et al., Nature 555, 220-222 (2018)

### 200.06 — Trajectory estimation for Benu’s particles

Steven R. Chesley<sup>1</sup>; Coralie Adam<sup>4</sup>; Peter Antreasian<sup>4</sup>; Brent J. Bos<sup>3</sup>; William V. Boynton<sup>5</sup>; Marina Brozović<sup>1</sup>; Brian T. Carcich<sup>4</sup>; Alex B. Davis<sup>2</sup>; Joshua P. Emery<sup>7</sup>; Davide Farnocchia<sup>1</sup>; Andrew S. French<sup>2</sup>; Carl Hergenrother<sup>5</sup>; Robert A. Jacobson<sup>1</sup>; Dante S. Lauretta<sup>5</sup>; Jason Leonard<sup>4</sup>; Erik Lessac-Chenen<sup>4</sup>; Andrew J. Liounis<sup>3</sup>; Jay McMahon<sup>2</sup>; Michael C. Moreau<sup>3</sup>; Michael C. Nolan<sup>5</sup>; William M. Owen<sup>1</sup>; John Pelgrift<sup>4</sup>; Benjamin Rozitis<sup>6</sup>; Daniel Scheeres<sup>2</sup>; Sanford Selznick<sup>5</sup>; Yu Takahashi<sup>1</sup>

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On Dec. 31, 2018 the OSIRIS-REx spacecraft entered orbit around its sample return target, near-Earth asteroid (101955) Benu. Optical navigation images taken less than a week after orbit insertion revealed

that the asteroid was emitting centimeter to decimeter sized particles, many of which immediately escaped from Benu. The mission team quickly began to tailor observations in order to better monitor the Benu environment for additional ejection events and particle tracking. This monitoring effort revealed that, in addition to those ejected directly onto hyperbolic orbits, some ejected particles returned to the surface on sub-orbital trajectories, while others entered relatively long-lived orbits, up to five days and over a dozen revolutions. This talk will describe the process of linking particle detections into datasets sufficient for orbit estimation, as well as the technical approaches and dynamical models used in the orbit estimation process.

## 201 — Dynamics of the Outer Solar System

### 201.01 — Computationally and Observationally Constraining the Outer Solar System Perihelion Gap to Help Find Planet X

William Jared Oldroyd<sup>1</sup>; Chad Trujillo<sup>1</sup>

<sup>1</sup> Physics and Astronomy, Northern Arizona University (Flagstaff, Arizona, United States)

In recent years, there have been several studies showing evidence for an undiscovered giant planet in the outer solar system (sometimes referred to as Planet X or Planet 9). Efforts to constrain the on-sky location of this planet have been made, but, thus far, the planet has escaped detection. The most distant objects in our solar system have elongated and inclined orbits and the orientation of their orbits is one of the primary evidences for the undiscovered giant planet. Intriguingly, no solar system objects have perihelia between ~50-65 au, yet bodies are known with perihelia less than and greater than this range. This perihelion gap has the potential to provide additional constraints for the undiscovered planet, which will, in turn, aid in the search for this mysterious world. We constrain the observed perihelion gap utilizing computational N-body simulations where suites of test particles, seeded in and around the gap, are exposed to gravitational interactions of the Sun, the giant planets, and the undiscovered planet. These simulations are carried out for the age of the solar system (4.5 Gyr) using REBOUND. A wide range of planet and test particle parameters are explored and will be presented.

### 201.02 — Resilience of the Self-Gravity Instability to Precession

Alexander Zderic<sup>1</sup>; Ann-Marie Madigan<sup>1</sup>; Jacob Fleisig<sup>1</sup>  
<sup>1</sup> University of Colorado Boulder (Boulder, Colorado, United States)

Disks of eccentric orbits have a self-gravity instability that can explain Neptune detachment and argument of perihelion clustering observed in the extreme trans-Neptunian objects (Madigan & McCourt 2016 and Madigan et al. 2018). However, previous work on the instability has focused on a simplified system lacking the influences of the giant planets, an omission that could affect the instability. Here we emulate the presence of the giant planets by adding a quadrupole moment ( $J_2$ ) to the potential in systems otherwise susceptible to the self-gravity instability. We find that for a sufficiently large  $J_2$  the self-gravity instability is suppressed, and we derive how this critical  $J_2$  scales with disk mass, particle number, and initial orbital configuration to extrapolate our results to the solar system.

### 201.03 — Positions of the secular resonances in the primordial Kuiper Belt disk

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In current dynamical evolution models aiming at reproducing the orbital structure of the Kuiper Belt, the giant planets start from a compact multiresonant orbital configuration and migrate to their current positions by interacting with a planetesimal disk extending beyond the orbit of Neptune. In order to stop the migration of Neptune at 30 AU and to reproduce the distinction between the dynamically cold and hot populations, it is often assumed that the primordial planetesimal disk was divided into two parts: a massive disk extending from Neptune to 30 AU and a low mass extension of the disk extending beyond 30 AU, the outer limit of which is quite uncertain. Before the dynamical instability between the giant planets, which strongly depletes the mass of the planetesimal disk, the massive part of the disk can have a significant influence on the apsidal and nodal precessions of the giant planets and of the planetesimals, leading to the shift of the positions of the secular resonances. In particular, the presence of the massive disk removes the degeneracy of the f5 nodal frequency and

allows for a new secular resonance. We investigate these effects in the linear secular theory of Lagrange-Laplace and find the locations of the secular resonances for different orbital configurations. We show that during the pre-instability period, for some orbital configurations the f5 nodal secular resonance is located in the region where the primordial cold classical Kuiper belt formed. If the inclination between the plane orthogonal to the total angular momentum of the giant planets and the mean plane of the massive disk is high enough, this nodal secular resonance is efficient at rising the inclinations of objects located in it. Thus, this could be a potential solution for the problem of the low density of the cold objects in the region near 45-47 AU.

### 201.04 — Origin and Evolution of Long-Period Comets

Luke Dones<sup>1</sup>; David Vokrouhlicky<sup>2</sup>; David Nesvorny<sup>1</sup>

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<sup>2</sup> Institute of Astronomy, Charles University (Prague, Czechia)

Nesvorny et al. (2017) performed the first end-to-end, 4.5 billion year simulations of the formation and evolution of the cometary reservoirs, focusing primarily on short-period (Jupiter-family and Halley-type) comets. Here we report the results of our simulations of long-period comets (Vokrouhlicky et al. 2019). The calculations begin with 1 million test particles in a massive disk beyond Neptune, with Uranus and Neptune migrating in a "jumping Jupiter" model of the early dynamical instability (Brasser et al. 2009, Nesvorny and Morbidelli 2012, Nesvorny and Vokrouhlicky 2016). The simulations include the effects of the four giant planets, galactic tides, and passing stars. Some 5% of the particles survive for 4.5 Gyr, with 90% of those in the Oort Cloud. The populations of the inner and outer Oort Cloud are roughly equal. Francis (2005) inferred from LINEAR data that there were 11 long-period comets/year with perihelia  $< 4$  AU and absolute magnitude 10.9. Our simulations, which are calibrated to the Jupiter Trojan implantation efficiency from the original planetesimal disk, predicts about 4 such comets/year. If we assume the magnitude-size relationship from Sosa and Fernandez (2011), these are cometary nuclei with diameters  $> 0.6$  km. Beyond perihelion distances of 15 au, the number of comets increases rapidly, and the inner Oort Cloud is the dominant source beyond 20 au. Surveys such as LSST should soon reveal the true structure of the Oort Cloud (Silsbee and Tremaine 2016).

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### 201.05 — Not a simple relationship between Neptune’s migration speed and Kuiper belt inclination excitation

*Kathryn Volk<sup>1</sup>; Renu Malhotra<sup>1</sup>*

<sup>1</sup> *Lunar & Planetary Laboratory, The University of Arizona (Tucson, Arizona, United States)*

We examine the inclination excitation mechanisms for Kuiper belt objects captured into Neptune’s 3:2 mean motion resonance and the hot classical belt during Neptune’s outward migration. The widely dispersed present day inclination distributions in these populations have been interpreted as strong evidence that Neptune must have migrated slowly because slow migration allows for multiple scattering events to raise the inclinations of Kuiper belt objects. However, in our numerical simulations we find counter-examples that show that the degree of inclination excitation is not necessarily correlated with migration timescale. A deep analysis of the simulations finds that secular excitation of inclinations can play an important role in shaping the final inclination distributions, especially for Neptune’s 3:2 resonance which is located very near a strong inclination secular resonance in the Kuiper belt. In the simulations, the relative importance of scattering versus secular excitation depends on the selection of pre-migration initial conditions for the planets and how their eccentricities and inclinations are (made to) evolve during migration; these choices affect the secular architecture of the giant planets as they migrate. The degree of inclination excitation in the post-migration 3:2 and hot classical populations can be very sensitive to the planets’ initial conditions and to the simplifications adopted in the numerical model to make the simulations computationally tractable. We suggest that the inclination distribution of the Kuiper belt is not conclusive evidence for a slow migration speed of Neptune and that other lines of evidence are required to constrain migration speed.

### 201.06 — Candidate Resonant Family Members of the Dwarf Planet Haumea

*Benjamin C. N. Proudfoot<sup>1</sup>; Darin A. Ragozzine<sup>1</sup>*

<sup>1</sup> *Brigham Young University (Highland, Utah, United States)*

The dwarf planet Haumea in the outer solar system presents a challenge for collisional modeling with its near-breakup spin, two regular satellites, and a surprisingly compact collisional family. In our recent detailed analysis of the distribution of collisional family members, no self-consistent formation hypothesis was able to match all we know about the family (Proudfoot & Ragozzine 2019). Further classification and identification of Haumea family members (“Haumeans”) will improve our understanding the formation of the Haumea family. We will present our search for and study of candidate Haumeans that were and/or are influenced by mean motion resonances with Neptune. Though harder to identify dynamically, these resonant Haumeans could provide crucial constraints on the Haumea family formation event. For example, resonant Haumeans could shed light on proper element distribution of the Haumea family. They could also provide insights on the age of the family and/or its possible interaction with Neptune’s orbital migration.

## 202 — Dynamics of Stars

### 202.01 — Vertical Mass Segregation in Eccentric Nuclear Disks

*Hayden Foote<sup>1</sup>; Ann-Marie Madigan<sup>1</sup>; Aleksey Generozov<sup>1</sup>*

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Eccentric nuclear disks are a type of nuclear star cluster in which the stars lie on apsidally-aligned orbits in a disk around the central supermassive black hole. These disks can produce a high rate of tidal disruption events (TDEs) via secular gravitational torques. Here, we show that eccentric nuclear disks exhibit strong vertical mass segregation, in which massive stars sink to low inclinations through dynamical friction with a more numerous population of lighter stars. This results in a much higher TDE rate per star among the heavy stars ( $\sim 0.10$ ) than the light stars ( $\sim 0.06$ ).

## 202.02 — The Fate of Binaries in the Galactic Center: The Mundane and the Exotic

Alexander Patrick Stephan<sup>1,6</sup>; Smadar Naoz<sup>1,6</sup>; Andrea M. Ghez<sup>1</sup>; Mark R. Morris<sup>1</sup>; Anna Ciurlo<sup>1</sup>; Tuan Do<sup>1</sup>; Katelyn Breivik<sup>2</sup>; Scott Coughlin<sup>3,4</sup>; Carl L. Rodriguez<sup>5</sup>

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The Galactic Center (GC) is dominated by the gravity of a super-massive black hole (SMBH), Sagittarius A\*, and is suspected to contain a sizable population of binary stars. Such binaries form hierarchical triples with the SMBH, undergoing Eccentric Kozai-Lidov (EKL) evolution, which can lead to high eccentricity excitations for the binary companions' mutual orbit. This effect can lead to stellar collisions or Roche-lobe crossings, as well as orbital shrinking due to tidal dissipation. In this work, we investigate the dynamical and stellar evolution of such binary systems, especially with regards to the binaries' post-main-sequence evolution. We conduct a large Monte-Carlo simulation including the effects of EKL, tides, general relativity, and stellar evolution. We use the dynamical break-up of binaries by scattering interactions with passing stars as a time limit for our simulations. We find that the majority of binaries (~75%) is eventually separated into single stars, joining the large population of singles in the GC, while the remaining binaries (~25%) undergo phases of common-envelope evolution and/or stellar mergers. These mergers or common-envelope binaries can produce a number of different exotic outcomes, including rejuvenated stars, extended dusty gas cloud-like infrared-excess objects, stripped giant stars, Type Ia supernovae (SNs), cataclysmic variables (CVs), symbiotic binaries (SBs), or compact object binaries. In particular, we estimate that, within a sphere of 250 Mpc radius, about 7.5 to 15 Type Ia SNs, on average, per year should occur in galactic nuclei due to this mechanism, potentially detectable by ZTF and ASAS-SN. Likewise we estimate that, within a sphere of 1 Gpc<sup>3</sup> volume, about 10 to 20 compact object binaries form per year that could become gravitational wave sources. This compact object binary formation rate translates to about 15 to 30 events per year detectable by Advanced LIGO.

## 202.03 — Detecting Black Hole Dynamics in the Heart of Galaxies with LISA

Bao-Minh Hoang<sup>1</sup>; Smadar Naoz<sup>1</sup>; Bence Kocsis<sup>2</sup>; Will Farr<sup>3</sup>; Jess McIver<sup>4</sup>

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Stellar-mass black hole binaries (BHBs) near supermassive black holes (SMBH) in galactic nuclei undergo dynamical eccentricity oscillations due to gravitational perturbations from the SMBH. Previous works have shown that this channel can contribute to the overall BHB merger rate detected by the Laser Interferometer Gravitational-Wave Observatory (LIGO) and Virgo Interferometer. Significantly, the SMBH gravitational perturbations on the binary's orbit may produce eccentric BHBs which are expected to be visible using the upcoming Laser Interferometer Space Antenna (LISA) for a large fraction of their lifetime before they merge in the LIGO/Virgo band. As a proof-of-concept, we show that the eccentricity oscillations of these binaries can be detected with LISA for BHBs in the local universe up to a few Mpc, with observation periods shorter than the mission lifetime, thereby disentangling this dynamical merger channel from others.

## 202.04 — Rotation Period Evolution in Low-Mass Binary Stars: The Impact of Tidal Torques and Magnetic Braking

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The long-term angular momentum evolution of isolated low-mass ( $M < 1 M_{\text{Sun}}$ ) stars is controlled by magnetic braking, the torque exerted on stars due to the coupling of stellar winds to the surface magnetic field (e.g. Dunn 1961, Mestel 1968). In stellar binaries, however, tidal torques can dominate the angular momentum evolution for short orbital periods ( $P_{\text{orb}}$ ). We examine how tides, stellar evolution, and magnetic braking combine to shape the rotation period ( $P_{\text{rot}}$ ) evolution of low-mass stellar binaries with

$P_{\text{orb}} < 100$  d. We test a wide range of tidal dissipation parameters and two commonly-used equilibrium tidal models and find that many binaries with  $P_{\text{orb}} < 20$  d tidally-lock, and nearly all with  $P_{\text{orb}} < 4$  d tidally-lock into synchronous rotation on circularized orbits. At short  $P_{\text{orb}}$ , tidal torques produce a population of fast rotators that single-star only models of magnetic braking fail to produce, but are naturally created when tidal effects are included. Furthermore, we show that the competition between magnetic braking and tides can generate a population of subsynchronous rotators that persists for Gyrs, even in short  $P_{\text{orb}}$  binaries, a population that has been observed in the Kepler field by Lurie et al. (2017). Both equilibrium tidal models predict that binaries can tidally-interact out to  $P_{\text{orb}} \sim 80$  d, and one model predicts that binaries can tidally-lock out to  $P_{\text{orb}} \sim 100$  d. Tidal torques often force the  $P_{\text{rot}}$  evolution of stellar binaries to depart from the long-term magnetic braking-driven spin down experienced by single stars, revealing that  $P_{\text{rot}}$  is not be a valid proxy for age in all cases, i.e. gyrochronology methods can fail unless one accounts for binarity. We suggest that accurate determinations of orbital eccentricities and  $P_{\text{rot}}$ , especially for  $P_{\text{orb}} > 20$  d, can be used to discriminate between which equilibrium tidal models best describes tidal interactions in low-mass binary stars.

### 202.05 — Companion-driven evolution of massive stellar binaries

*Sanaea Cooper Rose*<sup>1</sup>; *Smadar Naoz*<sup>1</sup>; *Aaron Geller*<sup>2</sup>

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The majority of massive (OBA-type) stars reside in binary or higher-order systems. We consider the dynamical evolution of massive binary stars in the presence of a faraway companion. For dynamical stability, these triple systems must have a hierarchical configuration. We explore the effects of a distant third companion's gravitational perturbations on a massive binary's orbital configuration before significant stellar evolution has taken place ( $< 10$  Myr). We include tides and general relativistic precession. We run large Monte-Carlo realizations of massive hierarchical triples and find signatures of the birth conditions on the final orbital distributions. Specifically, we find that the final eccentricity distribution is an excellent indicator of its birth distribution. Furthermore, we find that the period distributions have a similar mapping for wide orbits. Finally, we demonstrate that the observed period distribution for approximately 10 Myr-old massive stars is consistent

with triple-body evolution. The dynamical evolution of these systems can lend insight into the origins of extreme phenomena such as X-ray binaries and gravitational wave sources.

### 202.06 — Eccentricity and the Hills Mechanism

*Aleksey Generozov*<sup>1</sup>; *Ann-Marie Madigan*<sup>1</sup>

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Binary stars in a galactic nucleus can be tidally separated by a central supermassive black hole (SMBH) via the Hills mechanism. One of the stars in the binary is ejected as a hypervelocity star, while the other is left in a bound orbit around the SMBH. This mechanism likely produced the S-stars in our own Galactic Center, and may have produced a similar population in M31. In this talk I will review the physics of the Hill's mechanism and discuss the underappreciated role of the initial binary eccentricity in the process. I will also discuss the subsequent evolution of the bound stars.

### 202.07 — From Ultra-wide Binaries to Interacting Binaries in the Field

*Erez Michaely*<sup>1</sup>

<sup>1</sup> *Astronomy, University of Maryland (Rockville, Maryland, United States)*

The galactic field is regularly considered as a collisionless environment. However, for ultra-wide binaries ( $> 1000$  AU) that the field is not collisionless. These binaries experience perturbations from random stellar fly-bys which can excite their orbital eccentricities. Once the eccentricity is sufficiently high the binary component interact and can produce exotic binaries. In this talk I present the theoretical model that describes the binary-single interaction, in the impulsive regime, in the field of a galaxy. Furthermore, two examples of these kind of interaction will be discussed: 1. The production rates of low-mass X-ray binaries from wide binaries in the field 2. A novel GW merger channel for binary black-holes (BBH) from wide BBHs. The merger rate is comparable to the lower value of the observed BBH merger rate. For both examples specific observational signatures are discussed.

### 202.08 — Distribution of Planetesimals During Stellar Encounters

*Nathaniel Wyatt Hotchkiss Moore*<sup>1</sup>; *Gongjie Li*<sup>1</sup>; *Fred Adams*<sup>2</sup>

<sup>1</sup> *Georgia Institute of Technology (Atlanta, Georgia, United States)*

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Most stars form in clusters where close encounters with other stars are common. Such encounters leave architectural imprints on the orbits of planetesimals. Here, we investigate the dependence of these features on incoming stellar orbital parameters. We explore the parameter space of stellar encounters using N-body simulations and find that stellar encounters can leave unique signatures in the inclination distribution of a debris disk (the analog of the Kuiper Belt). Analytical expressions have been obtained to describe the distribution of possible inclination excitations. We can apply these results to constrain the conditions in our Solar System Birth Cluster using ongoing and future observational surveys for objects in the outer Solar System (including DES, LSST).

## 203 — Dynamics of Galaxies

### 203.01 — Dynamics of Local Group Satellite Galaxies in the Era of High Precision Astrometry

*Ekta Patel*<sup>1</sup>

<sup>1</sup> *University of Arizona (Tucson, Arizona, United States)*

High-precision astrometric data from space observatories, such as the Hubble Space Telescope (HST) and Gaia, are revolutionizing our ability to study the Local Group. In this talk, I will describe how combining this 6D phase space information (derived from proper motions) with high-resolution state-of-the-art simulations allows us to revisit models of the Local Group's dynamical history and its future fate. In particular, Andromeda (M31) and a recent breakthrough that have yielded a revised orbital history for M31's HST proper motion measurements for most massive satellite galaxy, M33, shifting the paradigm away from morphologically motivated orbital models (Patel et al. 2017a). I will show that constraining the orbit of a massive satellite galaxy like M33 is crucial for reconstructing the assembly history of the M31 satellite system, refining estimates for the total mass of M31, and for testing LCDM predictions at small scales through searches for "satellites of satellites" around M33 (Patel et al. 2017b, 2018a, 2018b). Additionally, I will discuss how we have used Gaia DR2 to independently measure the proper motions of M33 and M31. These measurements show good agreement with M33's new orbital history and allow us to revisit the parameters of the future collision between the Milky Way and M31. As the next decade will yield even more high precision data for the M31 system, I will conclude by outlining how we can use M31 as a benchmark for next generation studies of galaxies beyond the Local Group in

the era of WFIRST, JWST, and LSST.

### 203.02 — Hot and Cold Exponential Galaxy Disks from Star and Gas Scattering

*Curtis Struck*<sup>1</sup>; *Bruce G. Elmegreen*<sup>2</sup>

<sup>1</sup> *Department of Physics & Astronomy, Iowa State University (Ames, Iowa, United States)*

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The near universality of exponential (or double exponential) surface brightness profiles in galaxy disks, over a wide range of masses and Hubble types, has been well documented observationally. Stellar scattering off bars and spirals, as well as secular radial migration induced by such waves, can contribute to evolving the surface profile, but the former does not explain exponential profiles in spiral-free dwarf irregular galaxies, while the latter does not seem efficient enough to modify whole profiles. We previously showed, using scattering simulations and analytical arguments that massive young disk clumps, or massive clouds and holes in dwarf galaxies, can scatter stars into an exponential profile. These disks tend to be thick, with fairly high velocity dispersions. More recent work shows that widespread fountain flows from young star-forming regions can produce an exponential profile in the dense interstellar gas. Stars subsequently formed from this gas inherit the exponential profile in a low dispersion thin disk.

### 203.03 — Using Kinematics to Discover an AGN Turning Off and On

*Julia Comerford*<sup>1</sup>

<sup>1</sup> *University of Colorado, Boulder (Boulder, Colorado, United States)*

We present the discovery of an active galactic nucleus (AGN) that is turning off and then on again. The AGN resides in the  $z=0.06$  galaxy SDSS J1354+1327 and the episodic nuclear activity is the result of discrete accretion events, which could have been triggered by a past interaction with the companion galaxy that is currently located 12.5 kpc away. We originally targeted SDSS J1354+1327 because its Sloan Digital Sky Survey spectrum has narrow AGN emission lines that exhibit a kinematic velocity offset of 69 km/s relative to systemic. To determine the nature of the galaxy and its velocity-offset emission lines, we observed SDSS J1354+1327 with Chandra/ACIS, Hubble Space Telescope/Wide Field Camera 3, Apache Point Observatory optical longslit

spectroscopy, and Keck/OSIRIS integral-field spectroscopy. We find a  $\sim 10$  kpc cone of photoionized gas south of the galaxy center and a  $\sim 1$  kpc semi-spherical front of shocked gas, which is responsible for the velocity offset in the emission lines, north of the galaxy center. By modeling the kinematics of the gas, we interpret these two outflows as the result of two separate AGN accretion events; the first AGN outburst created the southern outflow, and then  $<10^5$  yrs later the second AGN outburst launched the northern shock front. The AGN in SDSS J1354+1327 fits into the broader context of AGN flickering that includes observations of AGN light echoes.

#### 203.04 — Accurate Identification of Galaxy Mergers with Imaging and Kinematics

Rebecca Nevin<sup>1</sup>; Laura Blecha<sup>2</sup>; Julia Comerford<sup>1</sup>

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Merging galaxies play a key role in galaxy evolution, and progress in our understanding of galaxy evolution is slowed by the difficulty of making accurate galaxy merger identifications. Mergers are typically identified using individual imaging techniques, each of which has its own limitations and biases. The stellar kinematics more directly trace the dynamics of galaxies (independent of their visual morphologies) and can be powerful probes of their assembly histories. With the growing popularity of integral field spectroscopy (IFS), it is now possible to introduce kinematic signatures to improve galaxy merger identifications. I use GADGET-3 N-body/hydrodynamics simulations of merging galaxies coupled with SUNRISE dust radiative transfer simulations to create mockup stellar kinematic maps and images to match the specifications of the Mapping Nearby Galaxies at Apache Point (MaNGA) survey, which is the largest IFS survey of galaxies to date. From the mockup galaxies, I have developed the first merging galaxy classification scheme that is based on kinematics and imaging. I will discuss the strengths and limitations of the classification technique and my plans to apply the classification to the  $>10,000$  observed galaxies in the MaNGA survey. I will then discuss my plans to utilize these large samples of merging galaxies (of different stages and mass ratios) to advance our understanding of open questions related to galaxy evolution, such as how star formation and AGN triggering change for different stages and types of mergers.

## 300 — Dynamics of Rings

### 300.01 — Are moonlets hidden among the clumps in Saturn's innermost ring?

Joseph A'Hearn<sup>1</sup>; Matthew Hedman<sup>1</sup>; Douglas P. Hamilton<sup>2</sup>

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Saturn's D68 ringlet is the rings' innermost narrow feature. Four clumps that appeared in D68 in 2014-15 remained evenly spaced about 30 degrees apart and moved very slowly relative to each other (Hedman 2019, *Icarus*), which is reminiscent of the stationary configurations of co-orbital nearly equal-mass satellites (Salo & Yoder 1988, *A&A*). We therefore explore the possibility that the source bodies for these four clumps are in such a co-orbital configuration. The spacing between the clumps is somewhat smaller than one would expect for a configuration of four moons, and changing the mass ratios is unable to fix this. We therefore consider whether an unseen fifth object could account for the discrepancies in the angular separations and allow the system to reach stationarity (Renner & Sicardy 2004, *CMDA*). We find a range of possible longitudes where a fifth co-orbital object could be, as well as the mass ratios between the five objects for any specified longitude within these ranges.

### 300.02 — The shape of Saturn's outer B ring

Philip David Nicholson<sup>1</sup>; Matthew M. Hedman<sup>2</sup>; Richard G. French<sup>3</sup>

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It has long been known that the outer edge of Saturn's B ring is strongly perturbed by the 2:1 inner Lindblad resonance with Mimas (Porco et al. 1984), and suspected that this resonance is responsible for confining the outer edge of this ring (Goldreich & Tremaine 1978, Tajeddine et al. 2017). Cassini imaging and occultation data revealed a more complex picture, wherein the resonantly-forced  $m = 2$  perturbation exhibits a large-amplitude libration with a period of  $\sim 5.4$  yr and a radial amplitude of as much as 70 km (Hedman et al. 2010, Spitale & Porco 2010, Nicholson et al. 2014). In addition, there are free modes with  $m = 1, 3, 4$  and  $5$  (Spitale & Porco 2010, Nicholson et al. 2014) and amplitudes of 7–22 km. We have used the last seven years of Cassini occultation data to update our previous fits, extending our

coverage to span  $\sim 2.5$  libration periods. The new results are consistent with our previous fits, while also suggesting an additional normal mode with  $m = 6$ . Furthermore, optical depth profiles and Cassini images reveal that these radial distortions extend for at least 500 km inward from the B ring's outer edge. Using a large set of stellar occultations obtained by the Cassini VIMS instrument, we have searched for wavelike structures in this region. In addition to indications of periodic perturbations with  $m = 1$  and a radial wavelength of  $\sim 110$  km reported previously, we find evidence for what appears to be an axisymmetric (i.e.,  $m = 0$ ) wave propagating inwards from the ring's outer edge (Hedman & Nicholson 2019). Supporting evidence for such a wave is found in mosaics assembled from several Cassini imaging sequences. We suggest that this wave, along with similar ones seen at two other locations in Saturn's rings, are driven by non-linear interactions between multiple edge modes.

### 300.03 — Changes in Saturnian Ring Particle-Size Distribution after Satellite Passage

Rebecca Harbison<sup>1</sup>

<sup>1</sup> Physics & Astronomy, University of Nebraska – Lincoln (Lincoln, Nebraska, United States)

The behavior of ring material near the satellite-bearing gaps in the A Ring is shaped by several gravitational processes. Like the rest of the A Ring, self-gravity pulls material together into larger, temporary aggregates called 'self-gravity wakes'. However, regular passage of Pan and Daphnis in their respective gaps stirs up adjacent material in the ring into 'satellite wakes'. Theoretical work by Borden et al. (2011) show that the particle-size distribution is shaped by the velocity dispersion (such as caused by satellite wakes) determining which collisions between ring particles cause adhesion of small particles to larger ones, and numerical simulations by Lewis and Stewart (2005) show that 'satellite wakes' can disrupt 'self-gravity wakes' and the region a few tens of kilometers from the gap edge changes in time after a satellite passage.

During stellar occultations of Saturn's rings observed by Cassini, we have observed 'gap overshoots' or 'horns': places near a sharp edge of the rings, such as the gaps of A Ring, where the transmission of starlight appears to exceed unity. This excess light is due to starlight forward-scattered from the nearby ring into the detector and is dependent on the particle size distribution. Work by Becker et al. (2016) with UVIS occultations detected a possible change in the observed particle-size distribution in data taken

shortly after a Pan encounter but limited to a few data points. I will present particle size distribution models from dozens of VIMS occultations, confirming Becker's work at the Encke Gap, and explore the narrower Keeler Gap. This will allow us to test hypotheses of the time-variability of self-gravity wakes (and the particle-size distribution itself) near the gap edges, and to look for observational differences between the behavior of the distribution near each gap.

### 300.04 — Simulating Saturn's A ring edge with a single chain of gravitationally-interacting particles

Yuxi Lu<sup>1</sup>; Douglas P. Hamilton<sup>1</sup>; Thomas Rimlinger<sup>1</sup>; Joseph Hahn<sup>2</sup>

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The edge of the A ring, located 136,769 km from Saturn, has a 7-lobed pattern that appears and disappears every 4 years as the nearby satellites Janus and Epimetheus swap their orbital positions. While Janus is in the inner position, its 7:6 resonance from Janus is located only  $\sim 4$  km inside the ring. This excites the 7-lobed normal mode on the ring edge, and the feature disappears as Janus moves from the inner position to the outer. We wish to model this satellite-ring system and have, accordingly, developed a new code to do so. We modified the N-body code, *hnbody*, to simulate narrow rings and ring edges using a single chain of gravitationally-interacting particles. We have tested our code on isolated resonances and can reproduce normal mode patterns including the 7-lobed feature in the A ring. However, the outer portion of the real A ring is perturbed by several resonances. The four most important resonances are The Lindblad Eccentric Resonances from Janus and Epimetheus that affect the eccentricities and the Corotation Eccentric resonances from each satellite that primarily affect the semi-major axes. Moreover, these four resonances move rapidly as the satellites swap orbital positions. We apply our new code to simulate the A ring edge with both satellites present and we are able to study the global patterns on the ring due to the action of multiple resonances. In this talk, we will describe how the outer parts of A ring change over a Janus-Epimetheus orbital period in our simulations and we will compare our results to observations.

### 300.05 — Stability of One Dimensional Rings of Gravitationally Interacting Masses

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The narrow rings of Saturn, Uranus, and Neptune orbit at distances of  $\sim 100,000$  km and have widths of just a few km, suggesting that they might profitably be modeled as one-dimensional chains of masses. We investigate the promise and the limitations of these models by exploring the effects of particle-particle gravity. One dimensional models can be made extremely efficient by neglecting all but the dominant forces arising between the nearest dozen or so neighbors in a chain. We routinely run simulations with thousands of masses, with increases in speed of factors of tens to hundreds over a direct  $N^2$  calculation of interparticle forces. Conversely, utilizing a single chain of particles suppresses all of the important effects that depend on interactions between neighboring streamlines, and so applications for a single chain of particles are limited.

In our first set of experiments, we initialize rings composed of  $N$  equally-spaced low masses with un-inclined circular orbits and follow their subsequent evolution as the masses are adiabatically raised. We find that instability invariably sets in when masses increase to the point that particle Hill radii reach  $\sim 25\%$  of the azimuthal particle spacing. This effect limits the total ring mass that may be modeled by a single chain of  $N$  particles and it also limits the number of individual particle that may comprise a given ring.

We also initialized our particle chains with different normal modes and studied the self precession of the resulting structures. While each configuration has given nodal and apsidal precession rates that we can calculate analytically, we find that splicing the ring mass into smaller and smaller bits does not lead to convergence of the precession rate to fixed values as might initially be expected. Since splicing a given ring mass ever more finely inevitably leads to full instability, however, it is not surprising that ring precession rates do not converge during this process.

### **300.06 — A Variational Principle for Self-Gravity Wakes and Spiral Density Waves**

*Glen Robert Stewart*<sup>1</sup>

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An important limitation of the Streamline Model for density waves in planetary rings is the complete neglect of local gravitational instabilities which lead to

the formation of self-gravity wakes in the A and B rings of Saturn as well as the formation of straw-like textures in the troughs of strong density waves and super-sized self-gravity wakes near the edges of satellite-perturbed ring edges, such as the Encke gap edge and the outer B ring edge. These local structures have significant pitch angles relative to the azimuthal direction, so they can be much more efficient at transporting angular momentum compared to binary particle collisions. I will present a variational principle for density waves that can describe the formation of local gravitational instabilities in the wave train. This has been achieved by modifying a variational principle derived by Alain Brizard for gyrokinetic plasma physics problems. The objective of gyrokinetic theory is to obtain a reduced description of the plasma where the fast gyro-motion of charged particles about the background magnetic field has been transformed away by using Lie-transform based Hamiltonian perturbation theory. My planetary rings version of the variational principle uses the same Lie-transform method to transform away the fast orbital motion of the ring particles in order to obtain a reduced description of the dynamics that is similar, but more general than the traditional Streamline Model. In particular, local gravitational instabilities are not thrown away as in the Streamline Model, but rather are transformed into terms in the variational principle that are analogous to the ponderomotive potential in plasma physics. In the absence of resonant forcing by a satellite, the variational principle recovers the integral equation for self-gravity wakes in the form presented by Fuchs (2001), which is equivalent to the original Julian and Toomre (1966) theory. The variational principle also facilitates an easy derivation of the angular momentum flux caused by the self-gravity wakes and the associated enhanced “viscosity” described by Daisaka et al. (2001).

### **300.07 — Rings around irregular bodies: a rich zoo of resonances**

*Bruno Sicardy*<sup>1</sup>

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Dense and narrow rings have been discovered in 2013 around the small Centaur object Chariklo (Braga-Ribas et al., *Nature* 508, 72, 2014), and around the dwarf planet Haumea in 2017 (Ortiz et al. *Nature* 550, 219, 2017). This came as a surprise as rings had been only known the around giant planets until then.

Due to their irregularities, small bodies exert strong resonances on a surrounding collisional disk.

In particular, non-axisymmetric terms in the potential of the body create sectoral resonances of the form  $j \kappa = m (n - \Omega)$ , where  $\kappa$  and  $n$  are the epicyclic frequency and the mean motion of the particle, respectively,  $\Omega$  is the rotation rate of the body, and  $j$  and  $m$  are integers ( $j$  being non-negative). In those circumstances  $n/\Omega \sim m/(m-j)$ , which is referred to as a  $m:m-j$  resonance.

Because non-axisymmetric terms for small bodies are relatively much larger than for giant planets, higher order resonances must be considered. Also, retrograde resonances are relevant because rings around small bodies may have been created after an impact, with no preference for prograde over retrograde motions.

Here we present various results related to the nature and dynamics of the sectoral resonances: (1) In general,  $j$  is the order of the resonance, i.e. the order of the leading term in eccentricity of the corresponding perturbing term. However, this requires some care when labeling the resonances. (2) A resonant orbit crosses itself  $|m|(j-1)$  times if  $m$  and  $j$  are relatively prime. This has important consequences on the structure of the streamlines near a resonance and the physics of a collisional ring. (3) Simple rules to calculate the strength of a  $m:m-j$  resonance are provided. (4) Prograde and retrograde resonances can actually be described in a unique frame. For instance the 1:3 and -1:1 (retrograde co-orbital) resonances have the same dynamical structure. (5) Examples of phase portraits of first, second, third and fourth order resonances are given. Their topology and implications for Chariklo and Haumea's rings are discussed.

The work leading to these results has received funding from the European Research Council under the European Community's H2020 2014-2020 ERC Grant Agreement n°669416 "Lucky Star".

## 301 — Dynamics of Lunar Probes

### 301.01 — The dynamical demise of Luna-3

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Luna-3 was a Soviet spacecraft launched in October 1959 on a nearly polar, highly elliptical orbit with

a semi-major axis of 0.7 lunar distance. After performing a lunar flyby, it collided with the Earth in late March 1960. Such a short dynamical lifetime has been ascribed in the literature to the increase in eccentricity due to Lidov-Kozai dynamics. However, considering that the Lidov-Kozai solutions are strictly valid for orbits close to the primary in the circular, restricted three-body problem, whereas Luna-3's orbit is far from the primary and it also intersects the orbit of the perturber, we find that the orbit of Luna-3 is better understood in the context of the Earth-Sun-Moon-spacecraft four-body problem. In light of this, we carried out a dynamical investigation about the main factors affecting the evolution of its trajectory and its demise. We numerically integrate the osculating trajectory of the spacecraft from published ephemerides with a high-fidelity orbit propagation tool, and find excellent agreement with previous solutions. Additionally, a sensitivity analysis shows the dynamics to be regular under small variations in the initial conditions and are well described by considering lunisolar perturbations only; higher gravity harmonics and other physical perturbations have negligible effects. We compare the numerically propagated osculating trajectory to single- and double-averaged solutions. We find that the osculating evolution is heavily influenced by close encounters that cannot be reproduced with averaged approaches, and induce large impulsive changes in the semi-major axis, eccentricity and inclination. Under lunar perturbations alone, Luna-3's trajectory collides with the Earth after 200 days in the single- or double-averaged propagations but survives for more than 100 years in the non-averaged solution. All of these phenomena result in the trajectory diverging from the level curves of the double-averaged quadrupolar Hamiltonian in Lidov-Kozai diagrams. We deduce that the Lidov-Kozai ansatz is not sufficient to capture the complexity of translunar trajectories, whose evolution is dictated by an interplay of lunisolar perturbations of both low and high frequencies and close lunar encounters.

## 302 — Dynamics of Planetary Systems

### 302.01 — Mean motion resonance widths at low and high eccentricity

*Renu Malhotra<sup>1</sup>*

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Orbital resonances play an important role in the dy-

namics of planetary systems. Classical theoretical analyses found in textbooks report that the widths of first order mean motion resonances diverge for nearly circular orbits; and numerical analyses based on averaging of the disturbing potential report divergence of resonance widths at planet-grazing eccentricity. We examined the nature of these divergences with non-perturbative analyses using Poincare sections based on the circular planar restricted three body problem. At low eccentricity, we show that the apparent divergence of first order resonance widths is an artifact of the leading order perturbation theory; the true resonance width has an asymmetry and a discontinuity around the nominal resonance location and a non-trivial transition to neighboring resonances. At planet-grazing eccentricity the divergence of resonance widths is shown to be an artifact of the single resonance approximation; the true resonance width is finite and, for first order resonance, scales as  $\sim\mu^\beta$  where  $\mu$  is the perturber's mass and  $\beta$  is  $\leq 0.5$ . Furthermore, for orbits of planet-crossing eccentricity there exists a second resonance libration zone whose libration center is displaced from the classical one at low eccentricity known from perturbation theory. We will illustrate these insights with applications to the asteroid belt and the Kuiper belt.

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### 302.02 — Collision rates of planetesimals near mean-motion resonances

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In circumstellar disks, collisional grinding of planetesimals produces second-generation dust, which can be observed through its thermal emission. While it remains unclear when second-generation dust first becomes a major component of the total dust content, the presence of such dust and potentially the substructure within it can be used to explore a disk's physical conditions. For example, a perturbing planet has been shown to produce nonaxisymmetric structures, as well as gaps in disks, regardless of the origin of the dust. However, small grains will have very different dynamics compared with planetesimals when in the presence of gas, and as such, the collisional evolution of planetesimals could create dusty disk structures that would not exist otherwise.

In particular, mean motion resonances (MMRs) are extremely nonlinear and could drive disk morphologies. We use a direct N-body model to track collision rates in a planetesimal disk under the gravitational influence of an external Jupiter-sized planet. The combined excitation and inward migration of planetesimals near MMRs tends to enhance the collision rate interior to the nominal resonance locations. This should produce observable variations in the radial structure of the dust, which could be used to infer the orbital parameters and mass of the perturbing planet. Because these simulations are very computationally expensive, we also compare with a model in which only a narrow annulus of material centered around the resonance is considered.

### 302.03 — The Solar wind as a sculptor of terrestrial planet formation

*Christopher Spalding*<sup>1</sup>

<sup>1</sup> *Astronomy, Yale University (New Haven, Connecticut, United States)*

The Kepler mission revealed that a substantial fraction of stars in the Galaxy possess planets residing on orbits that lie significantly closer to their host stars than Mercury does to the Sun. Furthermore, these close-in worlds typically exceed the Earth in size. Owing to the large amount of gas these bodies retain, they must have formed within the disk-hosting stage, lasting 1-10 million years. Our inner Solar system, on the other hand, is peculiarly deficient in mass, with absolutely no material detected interior to Mercury. The cause of the Solar system's hollowed-out architecture remains mysterious. Moreover, the Earth likely formed in 10s of millions of years, which is after the disk-hosting phase. In this talk, I will propose and test the hypothesis that the primordial wind emanating from the young Sun was sufficiently strong to remove planetary building blocks from interior to Mercury's orbit, with this material instead enriching the Earth's orbital vicinity with material from the high-temperature inner reaches of the Solar system. In this way, the mass deficit close to planet-hosting stars like our Sun arises as a natural consequence when planet formation occurs subsequent to the disk-hosting stage, as occurred in the Solar system. This wind-induced, outward migration of planetary building blocks predicts numerous compositional anomalies within the terrestrial planets and the asteroid belt that warrant further study. It further predicts relationships between exoplanetary sizes and orbital architectures that may be compared to forthcoming planetary detections.

### 302.04 — Dynamical Evidence for Terrestrial Planet Debris in the Asteroid Belt

*Claudia Maria Sandine*<sup>1</sup>; *Seth Andrew Jacobson*<sup>1</sup>

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The history of the solar system is dominated by collisions among large planetary embryos. Large planetary bodies form due to mass-gaining collisions that build up planets from small planetesimals to larger planet-sized objects, but these collisions also eject planetary material into orbit around the Sun. In the past, collisions between large planetary bodies were assumed to be perfectly accretionary. We have broken this assumption and incorporated a full collision model from Stewart & Leinhardt (2012) into our terrestrial planet formation simulations. Before this project, numerical simulations determined that leftover primitive planetesimals were emplaced in the asteroid belt. However, here we show that about 3% of the impact debris generated by collisions between planetary embryos during this early epoch was also emplaced in the asteroid belt. Furthermore, we tracked the transport history of planetary debris from its generation amongst the inner planets to stable orbits in the asteroid belt discovering that most debris is emplaced by a series of interactions with the outermost planetary embryo during periods when the embryo's aphelion entered the asteroid belt. The debris is emplaced on stable orbits throughout the asteroid belt across all relevant semi-major axes and inclinations; however, there is a paucity of very low ( $e < 0.1$ ) eccentricity debris objects. While these results utilized a suite of 52 simulations within the Grand Tack scenario, this result should be generic to all terrestrial planet formation scenarios that have planetary debris generating impacts and embryos whose eccentricity excursions bring the body into the asteroid belt to lift the perihelions of debris objects. While a small fraction of the debris is emplaced on stable orbits in the asteroid belt, most debris from planetary collisions in the inner solar system ends up in either the Sun (33%) or a planet (64%); also, about a quarter of the debris is re-accreted by the planet from which it was blasted off. From this work, we conclude that there must be pieces of planets in the asteroid belt.

### 302.05 — Losing moons: The gravitational influence of close encounters on satellite orbits

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The early solar system was a period of ubiquitous collisions and close encounters between protoplanetary masses, all coalescing to form our current four terrestrial planets. Earth and Mars have satellites likely formed by giant collisions, but Venus and Mercury do not despite forming in the same environment and possessing similar collisional histories as Earth and Mars. Large collisions routinely produce disks from which moons will accrete (Rufu et al. 2017). In particular, it is curious given the similarities between Earth and Venus in mass and orbital characteristics that Venus does not possess a moon while Earth possesses one. One possible reason for this discrepancy is that moons formed from giant impacts are later lost due to extended exposure to gravitational perturbations from close encounters with other protoplanetary masses. Analogously, these perturbations are thought to be responsible for the Moon's five-degree orbital inclination, in contrast to the physically-expected alignment with the equatorial plane (Pahlevan & Morbidelli, 2015). Further exposure to close encounters may alter inclination and eccentricity enough to liberate moons from their orbits. Here, we model the chaotic period of terrestrial accretion and moon formation to analyze the frequency and orbital influence of close encounters. We find that close encounters are plausible mechanisms for altering moon orbital characteristics. If the exposure to close encounters is long enough (i.e., if the moon was early-forming), the moon may be completely removed from its orbit. We apply these results to Venus' early history and to generalized terrestrial planetary formation histories. These results demonstrate that the timing of the moon-forming giant impact helps explain the retention and orbital characteristics moons.

## 303 — Dynamics of Exoplanets

### 303.01 — Excitation of Planetary Obliquities Through Planet-Disk Interactions

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The tilt of a planet's spin axis off its orbital axis ("obliquity") is a basic physical characteristic that plays a central role in determining the planet's global circulation and energy redistribution. Moreover, recent studies have also highlighted the importance of obliquities in sculpting not only the physical features

of exoplanets but also their orbital architectures. It is therefore of key importance to identify and characterize the dominant processes of excitation of non-zero axial tilts. Here we highlight a simple mechanism that operates early on and is likely fundamental for many extrasolar planets and perhaps even Solar System planets. While planets are still forming in the protoplanetary disk, the gravitational potential of the disk induces nodal recession of the orbits. The frequency of this recession decreases as the disk dissipates, and when it crosses the frequency of a planet's spin axis precession, large planetary obliquities may be excited through capture into a secular spin-orbit resonance. We study the conditions for encountering this resonance and calculate the resulting obliquity excitation over a wide range of parameter space. Planets with semi-major axes in the range  $0.3 \text{ AU} < a < 2 \text{ AU}$  are the most readily affected, but large- $a$  planets can also be impacted. We present a case study of Uranus and Neptune and examine whether this mechanism can help explain their high obliquities.

### 303.02 — Obliquity Evolution of Earthlike planets in $\alpha$ Centauri AB

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Changes in planetary obliquity, or axial tilt, influence the climatic conditions on a potentially habitable planet, where orbital perturbations from a binary star companion can drive these changes to extremes. We study the evolution of planetary obliquity for an Earthlike planet in the habitable zones of  $\alpha$  Centauri AB, our nearest stellar neighbor, through numerical simulations. Additionally, we explore the effects on the spin precession due to terrestrial neighbors and the presence of a moon. From our simulations, we uncover low variability regions of phase space that depend on the secular orbital precession as well as starting values for the mutual inclination relative to the binary planet, the spin longitude, and the initial obliquity. Moreover, we find that the added precession from a large moon typically destabilizes the host planet's obliquity allowing up to  $\sim 40^\circ$  of variation. The consequences for climate on such worlds will be influenced by orbital, flux, and obliquity variations, where we will discuss and compare the variations on an Earthlike planet in  $\alpha$  Centauri AB with those in the solar system.

### 303.03 — Modeling the Architectures of Exoplanetary Systems using Clusters of Similar Planets

*Darin A. Ragozzine<sup>1</sup>; Matthias Y. He<sup>2</sup>; Eric B. Ford<sup>2</sup>*

<sup>1</sup> *Physics and Astronomy, Brigham Young University (Provo, Utah, United States)*

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With over 700 systems of multiple transiting exoplanets, the Kepler Space Telescope has provided powerful observational constraints on the orbital and physical properties of planetary systems. As planets in these systems often have multiple planets and concentrate at semi-major axes of  $\sim 0.1 \text{ AU}$ , we refer to them as Systems with Tightly-spaced Inner Planets (STIPs). A full understanding of the true underlying architectures of STIPs is challenging because of the observational selection effects of the transit method. We compensate for these selection effects by proposing a model for the architectures systems, implement a forward model to produce a population of STIPs, using Kepler DR25 data products to model Kepler's detection efficiency and to produce a synthetic catalog of simulated observations, compare these to Kepler's observed catalog to produce a figure-of-merit, and infer the model parameters (including uncertainties) that best match the Kepler data. We investigate a model where STIPs are composed of clusters of planets where the overall cluster parameters are drawn from power-laws, but the planets within a cluster have similar periods and radii. Using advanced statistical techniques to incorporate a variety of observational constraints, we show that this clustered model performs much better than a non-clustered model, particularly in matching the observed period ratio and depth ratio distributions. We confirm previous results that most STIP planets are not near resonances and that the observed excess of single transiting planets implies that matching the Kepler data requires at least two types of planetary systems, with the higher-multiplicity system characterized by low eccentricities ( $\sim 0.01$ ) and mutual inclinations ( $\sim 1$  degree). We will present our model, the results of our fitting procedure, and the implications for STIP architectures.

### 303.04 — Dynamical Constraints on Planetary Systems: Multi-Planet Systems Observed with Single Transits

*Fred Adams<sup>1</sup>; Juliette Becker<sup>1</sup>*

<sup>1</sup> *Physics Department, University of Michigan (Ann Arbor, Michigan, United States)*

Transit surveys are discovering enormous numbers of extrasolar planets, with a sizable fraction found in multi-planet systems. Given the limitations on observational resources, especially the available time baselines, many planets are observed via single transit events. This talk describes how dynamical stability considerations can be used to constrain the allowed parameter space for such planetary systems in the absence of complete data. In addition to planets that are detected, we can also constrain possibilities for unseen planets that could exist in these systems. The orbital elements of these planets cannot be determined exactly, but can be described in terms of probability distributions, which in turn depend on the priors used in the analysis. The nearby five-planet system HIP 41378, with its outer three planets first discovered through single transit events, is used as a test case.

### 303.05 — Unseen companions of V Hya inferred from periodic ejections

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<sup>1</sup> *Physics and Astronomy, UCLA (Los Angeles, California, United States)*

A recent study by Sahai et al (2016) found periodic, high-speed, collimated ejections (or "bullets") from the star V Hya, using data from the Hubble Space Telescope. The authors of that study proposed a model associating these bullets with the periastron passage of an unseen, substellar companion in an eccentric orbit and with an orbital period of  $\sim 8$  yrs. Here we propose that V Hya is part of a triple system, with a substellar companion having an orbital period of  $\sim 8$  yrs, and a tertiary object on a much wider orbit. In this model, the more distant object causes high-eccentricity excitations on the substellar companion's orbit via the Eccentric Kozai-Lidov mechanism. These eccentricities can reach such high values, leading to Roche-lobe crossing, producing the observed bullet ejections via a strongly enhanced accretion episode. For example, we find that a ballistic bullet ejection mechanism is consistent with a brown dwarf companion, while magnetically driven outflows are consistent with a Jovian companion. Finally, we suggest that the distant companion may reside at few hundreds AUs on an eccentric orbit.

### 303.06 — Dynamical Sculpting of Compact Planetary Systems

*Alysa Obertas<sup>1,2</sup>; Norman Murray<sup>2</sup>; Daniel Tamayo<sup>3</sup>*

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The Kepler mission found hundreds of multi-planet systems, many of which have four or more planets all with orbit periods under 150 days. These compact systems have survived for  $10^{11}$  to  $10^{12}$  orbits. These systems are not only dynamically old, but also dynamically cold. Transit durations and transit timing variations show that high multiplicity systems typically have small orbital eccentricities and mutual inclinations. Nbody integration suggest that observed systems are packed close to their dynamical limits, but the mechanism ultimately driving the long-term evolution is still not well-understood. In a previous study, we investigated the long-term stability of a set of compact five-planet systems. In addition to recovering the expected relationship between the survival timescale and initial orbital spacing in mutual Hill radii, we also saw survival vary by several orders of magnitude near period commensurabilities, suggesting that mean motion resonance (MMR) is driving the dynamical evolution of the most compact planetary systems. It is not clear whether this chaos arises from resonance overlap of adjacent pairs of planets, or from overlap of subresonances for individual pairs however. We will present our recent analytical and numerical work to explore and understand subresonance overlap in compact multi-planet systems.

### 303.07 — Low-Eccentricity Formation of Ultra-Short Period Planets in Multi-Planet Systems

*Bonan Pu<sup>1</sup>*

<sup>1</sup> *Cornell University (Ithaca, New York, United States)*

Recent studies suggest that ultra-short period planets (USPs), Earth-sized planets with sub-day periods, constitute a statistically distinct sub-sample of *Kepler* planets: USPs have smaller radii ( $1-1.4 R_{\oplus}$ ) and larger mutual inclinations with neighboring planets than nominal *Kepler* planets, and their period distribution is steeper than longer-period planets. We study a "low-eccentricity" migration scenario for the formation of USPs, in which a low-mass planet with initial period of a few days maintains a small but finite eccentricity due to secular forcings from exterior companion planets, and experiences orbital decay due to tidal dissipation. USP formation in this scenario requires that the initial multi-planet system

have modest eccentricities ( $\geq 0.1$ ) or angular momentum deficit. During the orbital decay of the innermost planet, the system can encounter several apsidal and nodal precession resonances that significantly enhance eccentricity excitation and increase the mutual inclination between the inner planets. We develop an approximate method based on eccentricity and inclination eigenmodes to efficiently evolve a large number of multi-planet systems over Gyr timescales in the presence of rapid (as short as  $\sim 100$  years) secular planet-planet interactions and other short-range forces. Through a population synthesis calculation, we demonstrate that the “low- $e$  migration” mechanism can naturally produce USPs from the large population of *Kepler* multis under a variety of conditions, with little fine tuning of parameters. This mechanism favors smaller inner planets with more massive and eccentric companion planets, and the resulting USPs have properties that are consistent with observations.

### 303.08 — The hot Jupiter period-mass distribution as a signature of in situ formation

Elizabeth Bailey<sup>1</sup>

<sup>1</sup> Caltech (Pasadena, California, United States)

More than two decades after the widespread detection of Jovian-class planets on short-period orbits around other stars, their dynamical origins remain imperfectly understood. In the traditional narrative, these highly irradiated giant planets, like Jupiter and Saturn, are envisioned to have formed at large stellocentric distances and to have subsequently undergone large-scale orbital decay. Conversely, more recent models propose that a large fraction of hot Jupiters could have formed via rapid gas accretion in their current orbital neighborhood. In this study, we examine the period-mass distribution of close-in giant planets, and demonstrate that the inner boundary of this population conforms to the expectations of the in-situ formation scenario. Specifically, we show that if conglomeration unfolds close to the disk’s inner edge, the semi-major axis - mass relation of the emergent planets should follow a power law  $\propto M^{-2/7}$  — a trend clearly reflected in the data. We further discuss corrections to this relationship due to tidal decay of planetary orbits. Although our findings do not discount orbital migration as an active physical process, they suggest that the characteristic range of orbital migration experienced by giant planets is limited.

### 303.09 — Determining Stability Conditions for Submoons Orbiting Exomoon Candidate: Kepler 1625-b-I

Marialis Rosario-Franco<sup>1,2</sup>; Billy Quarles<sup>3</sup>; Zdzislaw E. Musielak<sup>2</sup>; Manfred Cuntz<sup>2</sup>

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An intriguing question in the context of dynamics arises: Could a moon possess a moon itself? Such a configuration does not exist in the Solar System, although this may be possible in theory; Kollmeier & Raymond (2019) showed the critical size of a satellite necessary to host a long-lived sub-satellite, or submoon. However, the orbital constraints for these submoons to exist are still undetermined, where a critical parameter is how far from the host satellite can these submoons orbit. Previous studies (Domingos et al. 2006) indicate that moons should be stable out to a fraction of the host planet’s Hill sphere, which in turn will depend on the eccentricity and inclination of its orbit. Motivated by this, we have performed orbital integrations of the exomoon candidate Kepler 1625-b-I, a Neptune-sized exomoon candidate that orbits the Jovian planet Kepler 1625-b (Teachey & Kipping 2018). In our numerical study, we evaluate the orbital parameters where possible submoons could be stable by varying the eccentricity and inclination of their orbits. Moreover, we provide discussion on the observational consequences of observing these satellites through photometric or radial velocity observations.

## 304 — Dynamics of the N ( $\geq 3$ )-Body Problem

### 304.01 — Three-body stability limit at infinite time

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In the general three-body problem the initial phase space may be divided in two parts: a chaotic region where orbits can be described by statistical means over the long term, and the stable region where definite orbit behavior may be found e.g. by perturbation technique. The surface in phase space which separates the two regions is called the stability surface, and if measured in units of the closest encounter distance between the binary and the pericenter of the

initial third body orbit, it is called the stability limit. An expression for the stability limit  $Q$ , in units of the semi-major axis of the binary, was derived by us:  $Q = 10^{1/3} A [(f g)^2 / (1 - e_3)]^{1/6}$  where  $A = 2.4$ ,  $e_3$  is the eccentricity of the outer binary orbit and  $f$  and  $g$  are functions which at the limit of  $e = \cos i = m = 0$ , obtain  $f = g = 1$ . Here  $e$  is the binary eccentricity,  $i$  the inclination between the inner and the outer orbits, and  $m$  is the mass of the third body with respect to the binary mass (Mylläri et al. MNRAS, 476, 830, 2018). The factor  $10^{1/3}$  comes from the number of outer revolutions  $N = 10,000$  used to define stability; for any other number of revolutions the coefficient is  $N^{1/12}$ . This would imply that the stability limit goes to infinity at infinite time, i.e. when  $N$  becomes infinite. The question we address in this work is whether this is true. By extending orbit integrations to higher revolution numbers,  $N$  up to  $10^7$ , and by modifying the analytical theory, we show that the stability limit is always finite, at any  $N$ . When  $N$  goes toward infinity, the factor  $10^{1/3}$  approaches  $10^{1/2}$  in the formula above which makes  $Q$  only about a factor of 1.5 higher than at  $N = 10,000$ .

### 304.02 — Spatial Low-Energy Asteroid and Comet Transit Analysis

Rodney Anderson<sup>1</sup>; Paul W. Chodas<sup>1</sup>; Robert W. Easton<sup>2</sup>; Martin W. Lo<sup>1</sup>

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The  $L_1$  and  $L_2$  gateways are well known to be key to understanding the transit of natural bodies near planets in low-energy regimes. These types of transit trajectories are particularly interesting for studying the temporary capture of objects near Earth and Jupiter. Understanding their behavior is also important for exploring potential impacts of asteroid or comets with these planets. Previous work by Anderson, Chodas, Easton, and Lo (2016) analyzed these types of trajectories using isolating block methods (Anderson, Easton, and Lo, 2017) within the context of the planar circular restricted three-body problem (CRTBP) and found that many of the characteristics of transit trajectories observed in nature may be captured using this model. Comparisons of the source orbital elements of these types of trajectories with known bodies showed potential relationships to comets and asteroids in the case of the Sun-Jupiter and Sun-Earth/Moon barycenter problems, respectively. Given that these initial results showed potential relationships between the transit trajectories and

known bodies, further exploration has now been performed in the spatial CRTBP. For this analysis, the planar isolating block methods for computing transit through the region near the secondary (Jupiter or the Earth/Moon barycenter) were extended to the spatial problem. These results produce topological disks, or portals, in configuration space through which all transit trajectories must pass at a given energy. These topological disks are computed both exterior to the  $L_2$  point and interior to the  $L_1$  point. Given these disks, analyses of the transit trajectories in the spatial problem are completed and compared to the previous planar results. The source orbital elements of the transit trajectories are also computed for comparison with known bodies and to aid in guiding the search for these types of transit trajectories. In particular, trajectories that potentially loiter near the Earth for significant periods of time are identified and described.

### 304.03 — Operator splitting methods for numerical integration of weakly perturbed N-body systems

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Operator splitting methods have proven powerful tools for the numerical integration of N-body systems. Symplectic splitting schemes in particular revolutionized celestial mechanics through their long-term conservation of the system's Hamiltonian structure. However, many astrophysically relevant perturbations like tides and drag are dissipative, and the numerical properties of splitting schemes that include them are unclear. We argue that power series expansions of splitting scheme errors applied to symplectic algorithms generalize to dissipative systems, and use these to analyze the numerical behavior of dissipative splitting schemes.

### 304.04 — Solving N-body problems

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The N-body problem describes a wide range of astrophysical phenomena, ranging from planetary systems to dark matter haloes. Perhaps the most popular line of attack to solving the N-body ordinary

differential equations is to use Hamiltonian, or symplectic, integrators to approximate their solutions. Examples of codes that do this include MERCURY, SyMBA, the Wisdom—Holman map, GADGET, or MERCURIUS. There is perhaps confusion as to what a symplectic integrator actually is, because codes considered symplectic in some works are not considered symplectic in other works.

In this talk, I propose a new definition for symplectic integrators. In terms of differentiability class, the integrator must be  $C^{1,1}$ . I show an example where not satisfying this criteria makes a bound Kepler orbit become hyperbolic in less than 10,000 periods. In experiments for several Hamiltonians, periodic orbits did not exist when the criteria was not satisfied. Several popular codes do not satisfy this differentiability criteria. I show that, numerically, the code MERCURY is not symplectic, and gives unphysical dynamics in some cases. Our recent code, MERCURIUS, is designed to overcome this limitation.

The N-body Hamiltonian has differentiability class infinity and I argue symplectic integrators should also have this symmetry. I find that increasing the smoothness of a hybrid integrator from  $C^0$  to  $C^4$  improves the error of the Jacobi constant of a restricted three-body orbit by  $10^5$ . While the differentiability class of popular codes can be increased with little effort, for other cases where the integrator has non-smooth changes, such as those using block time-stepping, the differentiability class may be difficult to change.

References: arXiv:1903.04972, arXiv:1904.03364, and arXiv:1902.03684

## 400 — In Honor of the Contributions of Bill Ward

### 400.01 — The Formation of Planetesimals

*Andrew Youdin*<sup>1</sup>

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The quest to understand the origin of planetesimals, i.e. the gravitationally-bound, solid building blocks of planets, lies at the forefront of astrophysics and planetary science. Work by Bill Ward has an ongoing impact on the field, including (but not limited to) the seminal Goldreich & Ward (1973) paper. The central hypothesis of these works is that planetesimals assembled by the gravitational collapse of dense clumps of much smaller solids. Even with current observational facilities, this hypothesis cannot be directly proved. However the hypothesis

is more popular than ever, having converted even some ardent skeptics. More importantly, the hypothesis remains tremendously useful, as a way to develop physically consistent models of planet formation which can explain salient features of Solar System bodies and exoplanets. In this talk, I will present an overview of state-of-the-art planetesimal formation models, including those where the streaming instability acts to seed the gravitational collapse of planetesimals. I will emphasize how Bill Ward's contributions laid the foundation for recent developments, and how some of his ideas — on the secular mode of gravitational collapse in particular — still require further exploration.

### 400.02 — The Evection Resonance in the Earth-Moon system: Analytical analysis

*Robin Canup*<sup>1</sup>; *William Ward*<sup>1</sup>; *Raluca Rufu*<sup>1</sup>

<sup>1</sup> *Planetary Sciences Directorate, Southwest Research Institute (Boulder, Colorado, United States)*

As the initial Moon's orbit expanded due to tidal interaction with the Earth, it would have encountered the evection resonance when the precession frequency of the Moon's perigee equaled that of the Earth's solar orbit (e.g., Brouwer & Clemence 1961; Kaula & Yoder 1976; Touma & Wisdom 1998). Capture into evection excites the lunar eccentricity and can drain angular momentum from the Earth-Moon system, transferring it to Earth's heliocentric orbit. Touma and Wisdom (1998) modeled the capture of the Moon in evection for an Earth with an initial rotation period of 5 hr and the Mignard tidal model. In their simulations, the Moon's residence in evection is relatively brief, and results in only modest removal of angular momentum, i.e., a few percent of  $L_{EM}$ . In contrast, Čuk and Stewart (2012) used a different tidal model and found that if the initial Earth-Moon angular momentum ( $L_0$ ) was substantially greater than  $L_{EM}$ , capture into evection could have instead reduced  $L_0$  by up to a factor of two or more. This would allow for a broader range of Moon-forming impact scenarios, including high angular momentum impacts that can directly explain many of the observed Earth-Moon isotopic similarities (Čuk & Stewart 2012; Canup 2012).

We have developed an analytic model to track the evolution in evection using the Mignard tidal model. We show that as long as the resonance remains occupied (i.e. librations are damped), the Earth-Moon will approach a co-synchronous state, independent of the value of  $L_0$ . This state has a substantially lower angular momentum than  $L_{EM}$ , and is ultimately unstable, resulting in the eventual loss of the Moon due

to slow-down of Earth's spin by the Sun. The current Earth-Moon system implies either that capture into evection did not occur, or that escape occurred prior to this point. Escape can occur if the libration amplitude becomes large. We examine how the libration amplitude changes with time during evolution in evection, and identify stages where escape may occur as a function of the tidal parameters of the Earth and Moon.

#### 400.03 — The Evection Resonance in the Earth-Moon system: Numerical analysis

*Raluca Rufu<sup>1</sup>; Robin Canup<sup>1</sup>*

<sup>1</sup> *Space Sciences, Southwest Research Institute (Boulder, Colorado, United States)*

Moon formation by a high-angular momentum impact may offer a compelling mechanism to create a satellite that is compositionally similar to the silicate Earth without requiring an Earth-like impactor (Ćuk & Stewart 2012, Canup 2012). In such impacts, the Earth-Moon system's initially high angular momentum must be greatly reduced after the Moon forms. A possible angular momentum removal mechanism is the evection resonance with the Sun, which occurs when the period of precession of the lunar perigee equals one year (Touma and Wisdom 1998). Capture into evection excites the lunar eccentricity and angular momentum is transferred from the Earth-Moon pair to Earth's orbit around the Sun. However, previous studies have found contradicting outcomes (e.g., early vs. late resonance escape; Ćuk & Stewart 2012, Wisdom & Tian 2015), and varied angular momentum removal efficiency for different tidal models. Understanding such behaviors is important for assessing the likelihood of high-angular momentum lunar origin scenarios. We study the system's evolution using a numerical model. Our results show that both early and late resonance escapes are possible in different parameter regimes. For early resonance escapes we find that the system may enter a protracted quasi-resonance phase (reminiscent of the limit cycle found by Wisdom & Tian, 2015), in which the eccentricity oscillates about a value smaller than the stationary resonance eccentricity (Ward et. al 2019). We find that the final Earth-Moon system angular momentum, set by the timing of resonance/quasi-resonance escape, is a function of both the ratio of physical and tidal parameters in the Earth and Moon (A), and the absolute rate of tidal dissipation in the Earth. Large rates are preferred for a fluid-like post-impact Earth (Zanhle et al. 2015) and for these values the angular momentum removal is controlled purely by evection (late resonance escape). Moreover, our

results do not show a preference for obtaining a final angular momentum similar to that in the current Earth-Moon system.

#### 400.04 — Bill Ward's Contributions to Planet Formation and Migration

*John Papaloizou<sup>1</sup>*

<sup>1</sup> *DAMTP, University of Cambridge (Cambridge, United Kingdom)*

The fundamental theoretical developments in the field of planet formation and orbital evolution that were pioneered by Bill Ward will be reviewed. The areas covered range from how particles accumulate to form planetesimals to delineating how protoplanetary cores migrate in the protoplanetary disk. In the latter case he established the main forms of migration that are driven by generation of density waves: type I for embedded protoplanets and type II for gap forming protoplanets. He was the first to clearly show that type I migration, applicable to embedded protoplanets was predominantly directed inwards. Perhaps not as well known was his original 1991 formulation of the non linear coorbital torque known as the 'horse shoe drag'. This and elaborations of it have proved significant for understanding how migration may be halted in for example planet traps and thus constitute an important ingredient of low mass planet formation modelling.

#### 400.05 — Tilting Ice Giants With Circumplanetary Disks

*Zeeve Rogoszinski<sup>1</sup>; Douglas Hamilton<sup>1</sup>*

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The leading hypothesis to the origin of Uranus' and Neptune's large obliquities, the angle between the planet's spin-axis and its orbital plane, is giant collisions, with impact masses ranging from Mars-sized for Neptune to Earth-sized for Uranus. Collisions this big, however, should also leave a strong imprint on planetary spin rates. While a Mars-sized impactor would change spin rate at the 10% level, an Earth-mass strike could alter it by up to a factor of 3. The ice giants' near identical spin rates are statistically inconsistent with such large impacts and instead suggest a shared origin with gas accretion dominating the final spin rate (Batygin, 2018); this, however, tends to drive obliquities towards 0°. Furthermore, tilting Uranus beyond 90° requires at least two impacts in order to explain the prograde motion of its satellites (Morbidelli et al., 2012). Is there a way to reconcile the tension between ice giant spin rates and obliquities?

Hamilton & Ward (2004) posit that Saturn’s 27° tilt is caused by a secular spin-orbit resonance: a match between the precession frequencies of Saturn’s spin-axis and Neptune’s orbit. The advantage of this mechanism is that it preserves the spin-state of the entire planetary system as the planet tilts over. Uranus’ and Neptune’s spin precession frequencies are currently too slow for a similar resonance, but that may not have always been the case. The spin precession rate is enhanced by the circumplanetary disk which must have existed for Uranus and Neptune to acquire their H and He gas and inner satellites. The low gas content of the ice giants suggests that sizable circumplanetary disks existed for just a few Myrs as the solar nebula dissipated. We show that realistic disk profiles can speed up the ice giants’ spin precession rates to match their orbital precession rates. This resonance can be strong enough to tilt each planet by 30° - 50° on Myr timescales, providing an alternative origin for Neptune’s tilt and perhaps also half of Uranus’. We are currently tuning parameters to push Uranus to an obliquity of 70°. If successful, Uranus’ final 98° tilt could be a product of a subsequent Mars-sized collision, with the associated change to its spin rate limited to ~10%.

#### 400.06 — Multi-Gyr obliquity history of Mars retrieved using the bombardment compass

*Edwin Stephen Kite<sup>1</sup>; Samuel Holo<sup>1</sup>; Stuart Robbins<sup>2</sup>*

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Because the Solar System is chaotic, planet orbits cannot be deterministically reverse-integrated beyond ~100 Mya. Many geologic methods have been proposed to vault this fundamental barrier, but all are indirect. We present a direct method, which we term the bombardment compass, and apply it to Mars. Mars’ obliquity is currently ~25° but has changed dramatically over billions of years since solar system formation (e.g., Ward, 1973; Touma and Wisdom, 1993; Laskar and Robutel, 1993; Laskar et al., 2004). The dynamics of Mars’ obliquity are believed to be chaotic, and the historical ~3.5 Gyr (late-Hesperian onward) obliquity probability density function (PDF) is highly uncertain and cannot be inferred from direct simulation alone. We developed a new technique using the orientations of elliptical craters to constrain the true late-Hesperian-onward obliquity PDF. We developed a forward model of the effect of obliquity on elliptic crater orientations using ensembles of simulated Mars impactors and ~3.5 Gyr-long Mars obliquity simulations. In our

model (Holo et al. 2018), the inclinations and speeds of Mars crossing objects bias the preferred orientation of elliptic craters which are formed by low-angle impacts. Comparison of our simulation predictions with a validated database of elliptic crater orientations allowed us to invert for the best-fitting obliquity history. We found that since the onset of the late Hesperian, Mars’ mean obliquity was likely low, between ~10° and ~30°, and the fraction of time spent at high obliquities >40° was likely <20%.

#### 400.07 — Scanning Secular Resonance Theory and the Epoch of Giant Planet Migration

*Craig B. Agnor<sup>1</sup>*

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Ward (1981) introduced the concept of scanning secular resonances and showed that the observed orbital architecture of a system can be used to constrain earlier epochs of evolution. This work established a generalised framework for tracing the linear secular evolution of a planetary system through an epoch where the system’s gravitational potential is changing. The central ideas of this work have been broadly applied to cosmogonical theories. For example, scanning secular resonances in the early solar system may explain the excitation of Mercury’s orbit, constrain the dispersal of the gaseous nebula, account for the obliquity of Saturn, drive the excitation and clearing of primitive body belts, and inform the orbital structure and history of exoplanetary systems. In this presentation I will review key aspects of the scanning secular resonance framework of Ward (1981) and discuss how the fundamental ideas of this work can be used to gain insight into several aspects of giant planet migration in the solar system.

### 401 — Spin-Orbit Dynamics

#### 401.01 — Tidally-driven collapse of outer solar system binaries.

*David A. Minton<sup>1</sup>; Andrew Hesselbrock<sup>1</sup>*

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Small body binary systems are common throughout the solar system and are typically comprised of two similar mass bodies orbiting their mutual barycenter. Binary systems are particularly common in sub-populations of Kuiper Belt Objects (KBOs), and the prevalence of binaries may correlate with the dynamical excitation level of the sub-population, with

the Cold Classical population having a higher prevalence of observed binaries than the more excited populations. Recent observations by the New Horizons spacecraft revealed that the Cold Classical Kuiper Belt Object 2016 MU69 is composed of two flattened lobes. Here we investigate the mechanisms by which KBO binaries can be induced to undergo tidally-driven collapse and reconfiguration, forming contact binaries. We also investigate how this collapse process may provide source material for the rings observed around some Centaurs.

#### 401.02 — The Search for Spin-Orbit Resonances in the Pluto System

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During the New Horizons flyby of Pluto, it was observed that the four small moons, Styx, Nix, Kerberos and Hydra, have very unusual spin states. Whereas we might have expected the moons to be tidally locked, they are in fact all spinning at rates markedly faster than their mean motions. Also, all of the moons' rotation poles are misaligned with their orbital poles; several moons have obliquities near 90 degrees. We explore the possibility that these moons may be trapped in an unusual type of spin-orbit resonances driven by the influence of Pluto's very large, inner moon, Charon. In this situation, a spin-orbit resonance is defined by three different periods: the moon's rotation period, its polar precession period, and its synodic orbital period with Charon. The combination of high obliquity and nonnegligible polar precession plays a very large role in this analysis, leading to resonant spin rates that are very different from what one would have predicted if polar precession is ignored.

We are currently in the second year of Hubble Space Telescope observing program focused on the photometry and dynamics of Pluto's small moons. The recent data set, combined with earlier HST data obtained during 2010-2015, provides a very long baseline for determining each moon's rotation period. In addition, we see direct evidence for polar precession in the year-by-year variations of each moon's photometry, suggesting that several of the poles precess over periods of a few years. With direct measurements of all three relevant rates, we are now

able to test the hypothesis that these unusual resonances might be active. Although our observational results are not yet definitive, initial results are encouraging. We note that the model of high-obliquity moons that are both spinning and precessing explains the photometry better than the earlier hypothesis by Showalter and Hamilton (Nature 522, 45-49, 2015, doi:10.1038/nature14469) that these moons are in chaotic rotation.

#### 401.03 — Constraints on the Masses of Nix and Hydra

Simon Bernard Porter<sup>1</sup>; Robin Canup<sup>1</sup>

<sup>1</sup> Southwest Research Institute (Boulder, Colorado, United States)

Pluto and its five satellites is the most complex circumbinary system yet visited with a spacecraft. The central binary of Pluto and the very large satellite Charon is surrounded by four much smaller, almost coplanar satellites. Here we will present initial results of an effort to constrain the masses of Nix and Hydra, the two larger small satellites, based on both their mutual perturbations and their perturbations on the two smaller small satellites, Styx and Kerberos. These constraints use a reanalysis with Gaia DR2 of all available Hubble Space Telescope and New Horizons observations of the small satellites to provide extremely high precision absolute astrometry. The range of mass+orbit solutions which both fit this high-precision astrometry and which are dynamically stable over long timescales allows us to place constraints on the masses of Nix and Hydra. These masses can then be combined with the volume estimates for Nix and Hydra from New Horizons resolved imaging in order to estimate the densities of those satellites. Since the small satellites were likely created in the same giant impact that created Charon, constraining their densities provides a unique insight in the giant impact process.

#### 401.04 — Spin and orbit dynamics of unique Kuiper belt trinary Lempo

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Many Kuiper belt objects orbiting beyond Neptune are found in binaries with a variety of mass ratios, but the only objects with three or more components are Pluto, Haumea, and 47171 Lempo (1996 TC36).

While Pluto and Haumea are large objects with multiple small moons, the Lempo system is unique in the Kuiper belt (and the solar system) as a true trinary system: a close binary (both bodies having nearly identical mass) and a single moon orbiting the binary. Due to the unique configuration of the system, especially the similar masses of all three components, the orbits cannot be modeled using Keplerian dynamics, though an approximate double-Keplerian solution was presented in Benecchi et al. 2010. We are studying the spin and orbit dynamics of the Lempo system using our new n-quadrupole integrator SPINNY (SPIN+N-body). SPINNY accounts for the quadrupole gravitational components in the spin and orbital evolution of an arbitrary number of bodies. Similar to Correia 2018, we use SPINNY to investigate the spin and orbit dynamics of this system, in coordination with a parallel effort to infer the physical and orbital parameters of the three components using astrometric data. We will present the new SPINNY integrator and insights into the spin and orbit dynamics of the Lempo system.

**401.05 —  $\nu$ A 2-DOF triaxial model for the roto-orbital coupling in a binary system. The slow rotation regime**

*Sebastian Ferrer<sup>1</sup>; Antonio Cantero<sup>1</sup>; Francisco Crespo<sup>2</sup>; Jorge Zapata<sup>2</sup>*

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<sup>2</sup> Universidad de Bio-Bio (Concepción, Chile)

The Full Gravitational 2-Body Problem is far from being integrable and continues to be a challenge. From the analytical point of view, several approximations are studied ranging from fundamental astronomy to space mission applications. A classical approach, that we assume from now on is to consider the roto-orbital dynamics of a triaxial body around a primary homogeneous sphere. In this regard, the gravitational potential is commonly assumed to be the MacCullagh’s truncation, although several recent papers go further than this approximation. We investigate analytical approximations, integrable or not, that could drastically simplify the search for special families of periodic or quasi-periodic orbit, where the influence of the roto-orbital coupling is considered. In this regard, we have presented recently some results [2], [3]. Our formulation is in Hamiltonian form and the variables in which the model is expressed are crucial in order to get compact expressions and intuitive geometric insight. Our choice is variables referred to the total angular momentum [1], which carry out the elimination of the nodes. The model is

chosen from the MacCullagh’s approximation without averaging. More precisely we choose the terms of the potential with depends only on the orbital variable  $r$  and the angular variable  $\nu$ . Thus the Hamiltonian takes the form  $H = H(r, \nu, R, N)$  is a 2-DOF system made of the Kepler and free rigid body together with the mentioned simplified potential. We examine families of relative equilibria leading to constant and non-constant radius solutions. We focus on the regime of slow rotations of the triaxial body, an assumption that brings different scenarios from the classical free rigid body. These families of relative equilibria include some of the classical ones, including ‘conic’ trajectories reported in the literature and some new types showing the critical role played by the triaxiality. The applicability of our model is assessed numerically.

[1] J.M. Ferrandiz and M.E. Sansaturio, *Celest. Mech. Dyn. Astr.* 46 (1989), 307-320; [2] F. Crespo, F.J. Molero, S. Ferrer and D. Scheeres, *J. of the Astro. Sci* 65, (2018), 1-28; [3] F. Crespo and S. Ferrer, *Ad. in Space Research* 61 (2018), 2725-2739.

**401.06 — Relevance of Solar System Dynamics for Present-Day Studies of Planetary Atmospheric Circulations (and other Geophysical Phenomena)**

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An expression describing a non-tidal coupling of the orbital and rotational motions of extended bodies is derived in [Plan. Space Sci. 141, 1, 2017]. The orbit-spin coupling torque (or, ‘coupling term acceleration,’ CTA) is given by  $CTA = -c (dL/dt \times \omega_n) \times r$ , where  $dL/dt$  is the rate of change of the orbital angular momentum of the subject body with respect to inertial frames,  $\omega_n$  is the angular velocity of the rotational motion of the subject body, and  $r$  is a position vector identifying a specific location on or within the subject body. The leading coefficient  $c$  is a coupling efficiency coefficient, to be determined through comparisons of model outcomes with observations, which is typically constrained (by error estimates for numerical simulations of orbital motions) to be extremely small. In contrast to conventional tidal friction (i.e., “spin-orbit coupling”) models, the torque given by the above equation changes sign. This may lead to both positive and negative accelerations of the rotation. As with tidal friction, dissipative interactions within the body are an expected consequence, as are slow evolutionary changes in orbital motions (conserving total system angular momentum). Orbit-spin coupling is likely to be effective

over far larger distances than may be the case for tidal friction, where the torques have a dependence on the inverse 6<sup>th</sup> power of distance. Two studies incorporating the CTA within atmospheric general circulation models have appeared [Plan Space Sci. 141, 45, 2017; Icarus 317, 649, 2019]. A key objective was to determine whether the agreement between atmospheric observations and numerical modeling outcomes could be improved by including the CTA with a non-zero value of  $c$ . This question has been answered in the affirmative; the modified GCMs successfully reproduce Martian global dust storm conditions in the years in which such storms actually occurred, with ‘hindcast’ success rates approaching 80%. The orbit-spin coupling hypothesis offers many opportunities for new research, both focusing on currently open questions, and in connection with re-evaluations of the conclusions of prior studies.

## Posters — Poster Presentations

### P1 — A New Non-Recursive Approach for Calculating Satellite Orbital Positions

Leland Langston<sup>1,2</sup>

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Away with  $M = E \cdot \text{esin}(E)$  ! Determination of a satellite’s position is usually accomplished by solving Kepler’s equation using a recursive or iterative approach to solve the transcendental equation, followed by using Gauss’s equation. This approach is effective, but requires multiple calculations that take time to perform. Furthermore, iterative procedures cannot be easily implemented in spread sheets or other similar calculating methods. Solving Kepler’s equation in an iterative fashion has been the means of calculating the orbital positions of celestial bodies in elliptical orbits for almost 400 years. This paper develops a non-recursive technique for achieving the same objective. In addition, a set of ancillary equations for calculating the radial and tangential velocity of a planet or satellite is presented. This approach is simple, can be implemented within a spread sheet and greatly reduces the execution time in critical real-time digital signal processing applications.

### P2 — Derivation of Cosmic Acceleration Given Inward Unbounded Light-Speed in the Hubble Expansion

Thomas Chamberlain<sup>1</sup>

<sup>1</sup> University of California, Berkeley (Los Angeles, California, United States)

This work discusses how replacement of Einstein’s postulated isotropic light-speed in special relativity by inward unbounded light-speed - with  $c/2$  outward, in accordance with Einstein’s “round trip axiom” - in the Hubble expansion gives an emergent, outward increasing cosmic time-dilation that allows a derivation of cosmic acceleration, meaningful to leading order in the local universe. Special relativity is revised in this deeper theory resulting in extra terms (e.g., in the Maxwell equations) which nevertheless uphold empirical accuracy.

A follow-on relativistic joining of outward cosmic time-dilation with inward (baryon-based) gravitational time dilation allows derivation of emergent cosmic deceleration with a leading order  $r^{1/2}$  dependence. For distances less than about 100 million light-years (in the present epoch) emergent cosmic deceleration exceeds cosmic acceleration and becomes increasingly dominant.

The present deepening of special and general relativity may be falsified. Here I claim that application of the theory will substantially reduce the need for both “dark energy” and “dark matter” in the  $\Lambda$ CDM model. Should the need for “dark matter” in explaining wide-binary star rotation flattening [shown superfluous in the talk], spiral galaxy rotation flattening [shown superfluous in the talk], “too fast” galaxy-cluster dynamics and growth, as well as the CMB power spectrum not drop from  $\sim 5\times$  total baryonic matter to well below total baryonic matter, the theoretical development may be considered falsified. Similarly, should “dark energy” in explaining cosmic acceleration remain necessary [shown superfluous in the talk], the theory may be considered falsified. In this theoretical deepening, the many important successes of special and general relativity are preserved.

### P3 — Geocentric Proper Orbital Elements

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As near-Earth space gets more and more congested, the need for a classification scheme based upon scientific taxonomy is needed to properly identify, group, and discriminate resident space objects, as has been advocated recently. Debris or not debris

is one of the fundamental questions that has motivated these efforts over the past few years, yet the current approaches all suffer from one essential feature: dynamical ambiguity. Any attempt to classify space debris, say, into families cannot be based on the osculating elements, which, being in continual change as functions of time, do not clearly disclose any characteristic feature of the initial orbit or state vector. Mean orbital elements, such as those provided by the two-line element sets of the space object catalog, also do not leave a dynamical fingerprint of the object's inherent state, since they vary over longer (secular) timescales. It is striking that astrodynamical taxonomists have not hitherto looked beyond our terrestrial abode for the proper solution to this compelling genealogy problem; namely, to the asteroid belt, where small-body taxonomists now enjoy one hundred years of astronomical heritage. Asteroid families consist of swarms of fragments generated after energetic interasteroidal collisions in the distant past that result in the breakup of their progenitors. They are dynamically recognized by searching for clusters in the three-dimensional space of proper elements; parameters characterizing the asteroid orbits that are very close to fundamental invariants of motion, and thus keep a dynamical record of the initial proximity of the orbits generated by a catastrophic fragmentation event. The concept of proper elements has already been applied with success to the natural satellite systems of the outer planets; but the orbits of artificial Earth satellites and space debris, and their dynamical environments, differ so markedly from the classical problems presented by nature, rendering many of the time-honored methods of Solar-System celestial mechanics inapplicable. Here, we present a theory of proper orbital elements in the circumterrestrial context. This talk is dedicated to the memory of Andrea Milani, an encyclopedia of astronomical insight.

#### P4 — Cosinusoidal Potential as a Possible Solution to the Planet IX Problem

David Farnham Bartlett<sup>1</sup>; John Cumalat<sup>1</sup>

<sup>1</sup> Physics, University of Colorado (Boulder, Colorado, United States)

Einstein's 1918 paper extended his classic 1916 paper on General Relativity. In this extension Einstein achieved a steady state universe by adding the cosmological constant term to his general covariant theory. Einstein also showed that even non-relativistic theory could achieve a steady state universe if one made a linear modification to Poisson's equation. He called the addition of a term  $k_0^2 \varphi$  to Poisson's equation a "foil", not to be taken seriously. Here  $\varphi$  is the

gravitational potential and  $k_0$  is a constant having the dimensions of an inverse length. We choose to add a length scale  $k_0^{-1}$  to the general formalism of GR, thus creating a specific example of  $f(R)$  gravity. (Here  $R$  is the Ricci Scalar). If  $k_0^2$  is negative the potential of a point mass is  $\varphi = -GM/r \text{Cos}[k_0 r]$ . We express  $k_0$  in terms of the constants  $c$ ,  $G$ ,  $\hbar$ , the mass of the electron, and  $\alpha = 1/137$ :  $k_0 = \text{Sqrt}[3 G c] m^2 \alpha^4 / \hbar^{3/2}$ . This  $k_0$  yields a wavelength  $\lambda_0 = 2 \pi / k_0 = 383 \text{ pc}$ , a length which is long compared to the dimensions of the solar system, but short enough to permit flat rotation curves for galaxies. Expressed as an energy,  $k_0 = 10^{-25} \text{ eV}$ , an energy so small as to be consistent with the current limit on the identity of speeds of gravitational and electromagnetic waves. Our modification leads to an oscillating universe instead of the big bang. It also gives very strong local tidal forces which can explain the observed influence of the galactic center on the aphelia of planets, comets, and large members of the Kuiper Belt. We also choose a smaller  $k_{\text{em}} = (1/3) k_0$  for the mass of the photon.

#### P5 — Formation of Exponential Profiles from Stellar Scattering Investigated with N-body Simulations

Jian Wu<sup>1</sup>; Curtis Struck<sup>1</sup>; Elena D'Onghia<sup>2</sup>; Bruce G. Elmegreen<sup>3</sup>

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The exponential shape of radial surface brightness profiles of disk galaxies has been observed and known for decades. However, the physical mechanism of its formation is not well understood. Disturbances from bars and spiral arms, viscous accretion of gas, and interaction with surrounding galaxies can account for an exponential disk, but these existing theories all have limitations. Experiments with the N-body simulation code GADGET-2 show that exponential profiles can form out of various initial stellar density distributions in a disk containing massive scattering centers, which in a real galaxy can be massive clouds or stellar clusters. The timescale of the profile evolution is influenced by scattering center properties including mass, orbital radius, and spatial number density. Cold disks with local gravitational instabilities can trigger temporary phase mixing and violent relaxation, which accelerate profile changes towards an exponential. This may be re-

sponsible for fast establishment of exponential profiles in disturbed dwarf galaxies.

## **P6 — Simulations of Multi-component Splash Bridges in Direct Galaxy Collisions**

*Travis R. Yeager*<sup>1</sup>

<sup>1</sup> *Physics and Astronomy, Iowa State University (Ames, Iowa, United States)*

We use an inelastic particle code with shocks and cooling calculated on a subgrid level to study the gas in direct collisions between galaxy discs. The interstellar media (ISM) of the discs are modeled with continuous thermal phases. The models produce many unique structures, which are collectively called splash bridges. They range from central bridge discs to swirled sheets, which resemble those observed in interacting galaxies. These morphologies are sensitive to the rotation, relative mass, disc offsets, and the gas structure in the discs. In the case of the Taffy galaxies - NGC 12914/15, extensive observations have revealed radio continuum emitting gas, HI gas, hot X-rays from hot diffuse gas and more H<sub>2</sub> than exists in the Milky Way coexisting in the bridge. The origins of the H<sub>2</sub> and large asymmetric distribution of ISM are not clear. We show that for small disc impact parameters, multiple phases of ISM with densities over many orders of magnitude can be removed from their host galaxies into a Taffy-like bridge. The orientation of the discs initial overlap can have a great effect on the distributions of each phase of ISM after the collision. In some cases, the models also predict the creation of a possible ‘dark galaxy,’ a large flat region of dense ISM far from the stellar disc potential of either galaxy. Another important parameter, currently being modeled, is the relative angle between the discs upon impact. A library of expected splash bridge morphologies can be a powerful resource for future observations conducted on interacting galaxies.

## **P7 — High-resolution profiles of the Uranian rings from Voyager 2 radio occultation observations**

*Richard G. French*<sup>1</sup>; *Sophia Flury*<sup>1</sup>; *Jolene Fong*<sup>1</sup>; *Ryan Maguire*<sup>1</sup>; *Glenn Steranka*<sup>1</sup>; *Colleen McGhee-French*<sup>1</sup>

<sup>1</sup> *Astronomy, Wellesley College (Wellesley, Massachusetts, United States)*

On January 24, 1986, the radio occultation of Voyager 2 provided a detailed portrait of the nine main Uranian rings during both ingress and egress, revealing complex structural details at 50-m resolution ( $\lambda=3.6$  cm), after reconstruction from the diffraction-limited

observations (Gresh et al. 1989, *Icarus* 78,131-168). With the success of the Cassini mission in obtaining hundreds of high-resolution occultation profiles of Saturn’s rings, there is renewed interest in exploring the narrow sharp-edged Uranian rings as analogs of Saturn’s own ringlets, several of which are home to density waves and excited normal modes. To search for evidence of similar features in the Uranian rings, we have returned to the original raw Voyager 2 Uranus radio occultation data (kindly provided by Dick Simpson) and used our open-source Python code (hosted on GitHub at [https://github.com/NASA-Planetary-Science/rss\\_ringoccs](https://github.com/NASA-Planetary-Science/rss_ringoccs)) to produce diffraction-reconstructed profiles of all 18 ring detections. Our 50-m resolution profiles are in excellent agreement with those provided by the original Voyager team to NASA’s Planetary Data System, confirming the validity of our implementation of the diffraction reconstruction technique pioneered by Marouf et al. (1986 *Icarus* 68, 120-166). We have extended this effort to produce 20-m resolution optical profiles, with the goal of searching for regular fine-scale structure within the Uranian rings. Although noise-limited at high optical depths, the new profiles exhibit quasiperiodic structure within some of the rings, which we quantify using Morlet wavelet spectrograms. In a related effort, we have successfully reproduced Gresh et al.’s detection of an anomalously strong scattered signal from the egress  $\epsilon$  ring event, which has prompted us to search for similar signatures in the vicinity of Saturn’s own broad (100-km) wide ringlets. Our open-source radio science ring occultation analysis code, *rss\_ringoccs*, was developed with support from JPL provided by the Cassini mission to Saturn.

## **P8 — Collisional fragmentation as a source for early martian impactors**

*Carlisle A. Wishard*<sup>1</sup>; *David A. Minton*<sup>1</sup>

<sup>1</sup> *Earth, Atmospheric, and Planetary Science, Purdue University (West Lafayette, Indiana, United States)*

Many previous models of solar system evolution have suggested that the craters seen on the most ancient surfaces in the inner solar system were created by a late dynamical instability in the outer solar system. Clement et al. (2018) showed that an early dynamical instability, prior to the end of terrestrial planet accretion, could satisfy many constraints placed on the architecture of the solar system as well, or better than, a late dynamical instability. Their model successfully replicates the structure of the inner and outer solar system but does not currently provide a source for inner solar system impactors.

In this work, we show that collisional fragmentation during the accretion of the terrestrial planets can provide a source for inner solar system impactors. Impacts between growing terrestrial planets and smaller bodies, like planetesimals and planetary embryos, generate collisional debris. This debris creates a source of impactors that is localized and preferentially impacts one terrestrial planet over another. While previous work has been done to incorporate fragmentation into an early instability model (Clement et al. 2019), in this work we address the effects of fragmentation on the cratering history of the inner solar system, with a focus on Mars.

The cratering chronology of Mars is derived from the lunar cratering chronology, with the underlying assumption being that both bodies share a common impactor source. A consequence of this assumption is that the lunar cratering chronology is mirrored on Mars. In this work, we aim to separate the cratering histories of the Moon and Mars using the results of n-body simulations of terrestrial planet formation, after the occurrence of an early outer solar system instability, as described by Clement et al. (2018). These simulations are then coupled with collisional evolution and cratering models. We will explore possible martian cratering chronologies that are not derived from the lunar cratering chronology and compared these possible cratering chronologies to the observable martian cratering history.

### **P9 — Re-examining the rings of Uranus in the Voyager 2 images**

*Robert Chancia<sup>1</sup>; Matthew Hedman<sup>1</sup>*

<sup>1</sup> *Physics, University of Idaho (Moscow, Idaho, United States)*

We examine the decades-old Voyager 2 images of the Uranian rings and present the results of our search for evidence of known and expected perturbations from nearby moons. The  $\epsilon$ ,  $\delta$ ,  $\gamma$ , and  $\eta$  rings are known to fall near resonances with the small inner moons of Uranus. The narrow rings' resonant interactions with moons give rise to oscillating edge positions causing variations in width, that can result in azimuthal brightness variations. Structures resulting from high-wavenumber resonances with Cordelia, Ophelia, and Cressida have been detected in the rings' radial positions and widths using either extensive sets of occultation observations or with brightness variations in more recent Hubble data, but there have not yet been comparable results reported for each ring using the higher resolution Voyager imaging data. Measured azimuthal variations in the integrated reflectance of the rings may provide estimates of a perturbing moon's mass, a physi-

cal characteristic that remains poorly constrained for the inner Uranian moons.

### **P10 — Vertical Mass Segregation in Eccentric Nuclear Disks**

*Hayden Foote<sup>1</sup>; Ann-Marie Madigan<sup>1</sup>; Aleksey Generozov<sup>1</sup>*

<sup>1</sup> *Astrophysical and Planetary Sciences, University of Colorado Boulder (Boulder, Colorado, United States)*

Eccentric nuclear disks are a type of nuclear star cluster in which the stars lie on apsidally-aligned orbits in a disk around the central supermassive black hole. These disks can produce a high rate of tidal disruption events (TDEs) via secular gravitational torques. Here, we show that eccentric nuclear disks exhibit strong vertical mass segregation, in which massive stars sink to low inclinations through dynamical friction with a more numerous population of lighter stars. This results in a much higher TDE rate per star among the heavy stars ( $\sim 0.10$ ) than the light stars ( $\sim 0.06$ ).

### **P11 — The planar rigid two-body problem**

*Margrethe Wold<sup>1</sup>; John Thomas Conway<sup>1</sup>; Alex Ho<sup>1</sup>*

<sup>1</sup> *Department of Engineering Sciences, University of Agder (Grimstad, Norway)*

We report on ongoing work to model the motion of two extended, rigid bodies of constant density, and present preliminary results for the case of two spheroids and two disks sharing a common equatorial plane. Our method evaluates the mutual gravitational potential between the two bodies as surface integrals of analytical expressions (MacMillan 1930), thereby avoiding expanding the potential in spherical harmonics. The method is exact to within the geometry of the bodies, and does not suffer from truncation errors, and it can also be used for close encounters. We solve the equations of motion in the center of mass system using a Runge-Kutta integrator, and show examples of trajectories for the two bodies as well as how their energy and momentum evolves over time.

### **P12 — VPlanet: The Virtual Planet Simulator**

*Rory Barnes<sup>1,2</sup>; Rodrigo Luger<sup>2,3</sup>; Russell Deitrick<sup>2,4</sup>; Peter Driscoll<sup>2,5</sup>; Thomas Quinn<sup>1,2</sup>; David Fleming<sup>1,2</sup>; Hayden Smotherman<sup>1,2</sup>; Diego McDonald<sup>1</sup>; Caitlyn Wilhelm<sup>1,2</sup>; Rodolfo Garcia<sup>1,2</sup>; Patrick Barth<sup>6</sup>; Benjamin Guyer<sup>1</sup>; Victoria Meadows<sup>1,2</sup>; Cecilia Bitz<sup>1,2</sup>;*

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We present a software package called VPlanet that can simulate numerous aspects of planetary system evolution for billions of years, with a focus on habitable worlds. In this initial version, eleven independent models for internal, atmospheric, rotational, orbital, stellar, and galactic processes are included and coupled to self-consistently simulate terrestrial planets, gaseous planets, and stars. We describe these models and reproduce observations and/or past results. In our framework, only the relevant physics is applied to each member of the system, facilitating the rapid simulation of a wide range of planetary systems. A key feature of VPlanet is that the user can determine at runtime which physics to apply to an individual object, so a single executable can simulate the diverse phenomena that are important across a wide range of planetary and stellar systems. This flexibility is enabled by matrices and vectors of function pointers that are dynamically allocated and populated based on user input. VPlanet is publicly available and the repository contains extensive documentation and numerous examples, with code integrity maintained through continuous integration and periodic scanning for memory issues.

### P13 — Effect of the Yarkovsky transverse parameter on radar astrometry for asteroid (99942) Apophis

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We present results regarding the Yarkovsky effect on Apophis, using time-delay and Doppler shift radar astrometry obtained from Goldstone and Arecibo during its 2012-2013 close approach with the Earth [1]. Using TaylorIntegration.jl [2], we compute our

own ephemerides for a dynamical model of the Solar System and Apophis. The bodies included are the Sun, the eight planets, the Moon and Ceres, and Apophis as a (massless) test particle. We consider post-Newtonian accelerations between all bodies, oblateness effects from the Earth's  $J_2$ ,  $J_3$  and  $J_4$  zonal harmonics, oblateness effects from the Sun's  $J_2$  zonal harmonic, and a kinematic model for the orientation of the Earth rotational axis. In the equations of motion for Apophis we include a non-gravitational acceleration term accounting for the transversal Yarkovsky effect. We take the initial conditions for Apophis from JPL's solution #199 [3] at the reference epoch September 24, 2008 00:00:00.0 (TDB). For the rest of the Solar System bodies considered, we take initial conditions from the DE430 ephemerides at the same reference epoch (for Ceres, we used initial conditions from Horizons). After reducing the relativistic and solar corona contributions to the radar astrometry based on our dynamical model, and exploiting automatic differentiation techniques, we obtain the O-C residuals of time-delay and Doppler shift as polynomial expressions which depend on the parameter  $A_2$ . Using these expressions, we describe the influence of the Yarkovsky parameter, and propose the nominal value  $A_2 = -5.68443 \times 10^{-14} \text{ au/day}^2$ , which minimizes the mean square residuals.

References: [1] Brozović, M., et al., 2018, Goldstone and Arecibo radar observations of (99942) Apophis in 2012–2013. *Icarus*, 300, 115-128. [2] Pérez-Hernández J. A., Benet L., 2018, TaylorIntegration.jl: ODE integration using Taylor's method in Julia, <https://github.com/PerezHz/TaylorIntegration.jl> [3] JPL's solution #199 for Apophis was downloaded in SPK format using the smb\_spk script provided by JPL at <ftp://ssd.jpl.nasa.gov/pub/ssd/SCRIPTS/>. Retrieved March 30, 2019.

### P14 — Non-hierarchical Triple Dynamics and Applications to Planet Nine

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Three-body interactions have wide applications in astrophysics. For instance, Kozai-Lidov oscillation for hierarchical triples has been studied extensively and applied to a wide range of astrophysical topics.

However, non-hierarchical triples also play a dominant role but it is less explored. In this work we consider the secular dynamics of a test particle inside a non-hierarchical configuration with two massive objects. We find the resonances and chaotic regions using surface of sections, and we identify regions of phase space that allows large eccentricity and inclination variations. In the end, we apply our understanding to the distribution of extreme TNO under the perturbation of a possible Planet Nine.

### P15 — Nbody Simulations of Self Confining Ringlets

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Nbody simulations are used to explore whether narrow eccentric planetary rings might be self confining. In our experiments, the `epi_int_lite` Nbody code is used to evolve a viscous and self-gravitating ringlet that is represented as a pair of gravitating streamlines that interact via their mutual gravities and viscous friction. We find that the streamline's secular gravitational perturbations causes the streamline's eccentricity gradient  $e' = a(de/da)$  to grow over time while the ringlet's internal friction causes the streamlines to spread radially. And in certain circumstances, the simulated ringlet's eccentricity gradient approaches the critical value  $e' = \sqrt{3}/2 = 0.877$ , which zeros the orbit-averaged viscous torque that adjacent streamlines exert on each other (Borderies et al 1982). When that happens, the simulated ringlet's radial spreading slows dramatically but is not entirely halted. Rather, our simulated ringlet still spreads albeit very slowly while executing low-amplitude librations about the equilibrium state described in Borderies et al (1983). So our simulations show that a ringlet's secular gravitational perturbations can drive an unconfined viscous ringlet very close to the  $e' = \sqrt{3}/2 = 0.877$  threshold, which suggests that narrow eccentric planetary rings might be self-confining without the need for any shepherd satellites. But it is unclear today whether the low-amplitude libration and slow spreading seen in our simulation is real or somehow an artifact of subtleties in the `epi_int_lite` code or choice of initial conditions.

### P16 — Identifying Three-body Resonances in Kepler's Extrasolar Planetary Systems

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The Kepler Space Telescope discovered over 200 systems with three or more known exoplanet candidates. Previous studies have found that some exoplanetary systems contain three-body mean motion resonances which offer valuable insights into the formation, evolution, and dynamics of exoplanetary systems. Using the precise orbital periods from Kepler exoplanetary systems, we search for candidate three-body resonances by identifying commensurabilities in every possible set of three planet candidates. Since there are many opportunities for random three-body alignments, we assess the false alarm probability for the candidate three-body resonances in order to identify the most dynamically significant cases. Even though Kepler periods are known precisely (typically to one part in 100,000), we find that the observational uncertainties in the periods are important for identifying real three-body resonances. We will present the findings of our search for statistically significant Kepler three-body resonances.

### P17 — Towards a Photodynamical Analysis of Kepler's Multiply-Transiting Systems

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The Kepler Space Telescope discovered about 700 systems with multiple transiting exoplanets (about 1700 planet candidates) over a four year period. In systems of multiple transiting planets, planet-planet gravitational interactions can sometimes be detected by observing that the transits do not occur strictly periodically (sometimes called Transit Timing Variations or TTVs). Until now, planetary interactions have not been typically included in the determination of the full set of light curve parameters. We seek to increase the amount of information extracted from these exoplanetary systems with a more detailed analysis. In particular, by fitting the transiting light curves, we can better constrain exoplanetary masses (along with other orbital properties). In combination with the measured radii, these light

curves reveal densities of exoplanets that are crucial for understanding their formation, evolution, and habitability. We have started a new investigation aimed at these more precise measurements by connecting n-body integrations directly to the measured light curve (skipping the step of measuring individual transit times), using our new PhotoDynamical Multi-planet Model, PhoDyMM. Coupled with a Bayesian parameter inference method (Differential Evolution Markov Chain Monte Carlo), we plan to apply PhoDyMM to all 700+ systems of Kepler multiple transiting planets in order to infer physical and orbital parameters using the best existing data. We will present early results from this large project focused on the details of our specific methodology and application to test cases.

### **P18 — Size frequency distributions of impact craters on Saturn’s moons Tethys & Dione; implications for source impactors**

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Currently the Saturnian satellites are thought to have formed anywhere between 4.5 Gyr and 100 Myr. One constraint on the ages of these satellites is the impactor flux that is creating the craters on the satellites. We completed regional scale mapping (image resolutions of ~250 m/pix or better) on Tethys and Dione to investigate the distribution of small impact craters ( $D < 5$  km) and elliptical craters to investigate the source population of impactors in the system. Major sources of impactors in the Saturnian system are thought to consist of heliocentric and planetocentric debris, each of which could have been active at different periods in the history of these satellites. Our mapping on Tethys finds that we see an abundance of small impact features on the cumulative size frequency distribution (CSFD) and a steeper slope relative to the younger mapped terrain. Younger terrain units have shallower slopes that agree with a potential heliocentric population at small diameters. We interpret this difference in slope to be a transition from an initially planetocentric population that follows along with the Case B function from Zahnle et al. 2003, to a heliocentric population that matches well with Case A. We have also mapped the surface of Dione in four regions, each within a distinct geologic unit (unit descriptions via Kirchoff et al. 2015) using high-resolution Cassini data (image resolution ~250 m/pix). Analysis of Dione results finds similar size-frequency distributions to what was observed

in Kirchoff et al. 2015 for the fractured terrain and smooth terrain. Analysis of their potential source populations is ongoing and will be presented. We present our size-frequency results so that we can engage in further discussion with the dynamics community about the potential source populations for these impact craters.

### **P19 — Comparison of predictions of asteroids’ close encounters with the Earth**

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Prediction of future close encounters of asteroids with the Earth belongs to sensitive information as it has a direct relation to the possible collision with the Earth. Observations of asteroids collected by the IAU Minor Planet Center (MPC) generally constitute the same source of astrometric and radar measurements for orbital computations and subsequent close approaches. We report here on a cross-identification of such events between different lists of predictions provided by the well-known world professional services: IAU MPC (Forthcoming Close Approaches To The Earth and the Running Tallies), the JPL Center for NEO Studies (CNEOS), the ESA SSA-NEO Coordination Centre (NEOCC) through its Space Situational Awareness Programme, and DynAstVO, the newly opened service of IMCCE at Paris Observatory PADC centre. We have selected two one-year windows, separated by 4 months, for generating the lists of predictions. Each event that has declared calculated geocentric distance of close approach less or equal 0.05 AU in one of the lists was cross-identified with the events in other sources. The comparisons were made with respect to the orbital propagations provided by the JPL HORIZONS on-line solar system data and ephemeris computation service. It appears that the actual predictions made by all these services can be significantly different, not only in epochs and distances of close encounters, but also in the entry list of asteroids. We have found that in both comparison window cases, all the services produce predictions that agree in less than 50% cases with respect to the general set formed as a union of all tables. The highest overlapping belongs to DynAstVO and NEOCC while the lowest to IAU/MPC. These differences in the prediction lists may be explained by peculiarities of the algorithms used, frequency of

the orbital updates, different weighting schemes applied in the orbital determinations. We emphasize the necessity of additional astrometric/radar measurements of potentially hazardous asteroids, especially those which constitute the differences in such predictions.

## P20 — Could there be an Undetected Inner Planet Near the Stability Limit in Kepler-1647?

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Kepler-1647b is the most recently discovered planet that transits two stars, i.e., a circumbinary planet (CBP). Due to its large orbital separation, Kepler-1647b stands out from the rest of the Kepler CBPs, which mostly reside on much tighter orbits near the stability limit. The large separation of Kepler-1647b challenges inward disk migration as a dominant formation pathway, suggested by the other Kepler CBPs. In this paper, we consider the possibility of an undetected planet near the stability limit by examining observational consequences of such a planet. We calculate the transit probability of the putative planet, transit timing variations (TTVs) of the known planet, and eclipsing timing variations (ETVs) of the host binary caused by the putative planet. We find the presence of a  $\gtrsim 30 M_{\oplus}$  inner planet to be highly unlikely near the stability limit. In addition, we provide future TTV observation windows, which will further constrain possible undetected planets with lower masses.

## P21 — The Exact Boltzmann Most Probable Monatomic Ideal Gas

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New results are presented for Boltzmann's most probable dynamics of an ideal monatomic gas. His work is pivotal in the dynamical foundations of stellar systems and planetary & satellite atmospheres. Velocity space is divided into  $N_c$  cells of equal volume, cell  $j$  particles have population  $n_j$  & kinetic energy  $\epsilon_j$  each. Particles of mass  $m$  remain intact in collisions so total population  $N$  is constant. A collision can change particle energy but total system kinetic energy  $\hat{E}$  is constant.  $m, N$  &  $\hat{E}$  are defining constants of the gas. Macroscopic gas properties are due to its

macrostate, i.e. cell particle populations  $n_j$ . A microstate is given by each particle's cell location. Randomizing particle collisions cause an equilibrium macrostate which is due to the largest number of microstates obeying the  $N$  &  $\hat{E}$  constraints. Boltzmann's entropy  $S$  must then be maximized since it is the log of the microstates in a macrostate where  $S = \sum_{j=1}^{N_c} \ln(n_j!)$  (1).  $n_j$  satisfying these conditions are found by Lagrange's multiplier method whose equations are in unitless form if energy multiplier  $B$  defines unitless energies by  $e_j = B \epsilon_j$ ,  $E = B \hat{E}$  (2). The  $N_c + 2$  Lagrange unitless constrained extreme entropy equations are  $A = e_j + \Psi(n_j + 1)$ ,  $N = \sum_{j=1}^{N_c} n_j$ ,  $E = \sum_{j=1}^{N_c} e_j n_j$  (3) where  $A$  is the population multiplier &  $\Psi(n)$  is the digamma function defined by  $\Psi(n) := d(\ln((n-1)!)/dn$ . 2 approximations for the above situation are considered giving Case 1: the above exact case, using Boltzmann's entropy formula Case 2: is Boltzmann's use of Stirling's approximation in (1) giving  $A = e_j + \ln(n_j)$  Case 3: directly approximates  $\Psi(n_j + 1)$  giving  $A = e_j + \ln(\exp(-\gamma) + n_j)$ , For large  $n_j$  all cases obey  $A = e_j + \ln(n_j)$  At  $n_j = 0$  case 1 & 3 allow any  $A > 0$  but case 2 has  $A = \infty$  (3) gives  $\{E, N_c, n_j\}$  of  $\{A, N, e_j\}$ :  $A, nH$  (highest  $n_j$ ) or  $eH$  (highest  $e_j$ ) specify a macrostate  $eH = A + \gamma$ ,  $eH = \gamma + \Psi(nH + 1)$ ,  $\gamma$  is Euler's constant  $eH$  is a natural parameter for a  $n_j(e)$  distribution. The gas terminates at  $\{n_j = 0, e_j = eH\}$  with any  $eH > 0$  The following quantities are determined:  $VH(m, eH)$  gives the unitless phase space volume of gas phase points  $N_c(eH, N)$  gives the number of cells  $V_c(eH, m, N) = VH/N_c$  gives the cell size  $C(eH) = E/N_c$  gives specific heat ratio  $3/2$  for large enough  $eH$

## P22 — Planned archive of Uranus ring occultation observations on NASA's Planetary Data System

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Under NASA's PDART (Planetary Data Archiving, Restoration, and Tools) program, we are in the process of submitting the entire set of known high-SNR Uranus ring occultation observations to NASA's Planetary Data System Ring-Moon Systems Node (RMS). These observations span more than 25 years (1977-2002), and include digitally-recorded aperture photometry in the IR, several early events that were recorded only on strip charts, additional high-SNR unpublished ground-based observations, two occultations observed from the Hubble Space Telescope, and two occultations observed using 2D imaging arrays. The archive will contain the full continuous

time series observations of each occultation, as well as high-resolution individual ring event profiles registered on a radius scale based on a self-consistent ring orbit model accounting for the inclinations and eccentricities of the rings, all fitted normal modes, and a derived Uranus pole direction. We will submit all raw, intermediate, and higher order products to the PDS, along with complete documentation and machine-readable tables of key derived quantities for each observed occultation and ring profile. This will enable intercomparison with other planetary rings, such as Saturn's narrow ringlets, and allow systematic searches to be made for previously undetected rings or ring arcs in the Uranus system that may be associated with the dusty sheets of material associated with the rings, as seen in Voyager forward-scattering images. Once the data have been ingested into PDS, they will be accessible from the RMS Node, including being fully supported by the node's search tool, OPUS. The results will be useful for studies of the dynamics and kinematics of the rings and their internal structure, and for setting limits of the gravitational harmonics of Uranus itself, and hence its internal structure as well. Our target date for completing this work is August 31, 2020, and we invite suggestions from potential users so that the archived results will be as useful as possible to the entire scientific community. This work is supported by NASA's PDART program.