2017 DDA Meeting Abstracts

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Monday, June 12

Post Main Sequence Planetary System Science, Part 1 (Chair: Dimitri Veras)

Amy Bonsor, University of Cambridge
Dust around evolved stars; tracing the fate of planetary systems
Planetary systems are commonly observed around main-sequence stars. Almost all planet-host stars evolve to become giants, before ending their lives as white dwarfs. What is the fate of their planetary systems? I review the link between dust observed around giants and white dwarfs, the dynamical evolution of planetary systems and their fate beyond the main-sequence.
Roman Rafikov, University of Cambridge
Physics of the Compact Debris Disks Around Metal Rich White Dwarfs
Significant fraction of the white dwarfs are known to have metal polluted atmospheres, with a much smaller fraction (of order several per cent) also exhibiting near-infrared excesses, indicative of the presence of the dense debris disks in their immediate vicinity. Such disks are believed to originate from tidal disruption of the minor objects originally orbiting these white dwarfs, thus shedding light on the properties of the planetary systems hosted by these stellar remnants. They also provide an obvious mass reservoir to explain the observed metal contamination of the white dwarf atmospheres. In my talk I'll focus on the physical processes affecting the evolution of the debris disks and affecting the rate, at which they accrete onto their central stars. I will demonstrate the key role of the Poynting-Robertson drag in setting the minimum metal accretion rate onto the white dwarf. I will also show how the coupling between the particulate and gaseous debris disks can naturally give rise to much higher accretion rates of metals. Better understanding of these processes will help us illuminate accreton history of minor planets by the white dwarfs.
Rik Van Lieshout, Institute of Astronomy, University of Cambridge
Exoplanet recycling in massive white-dwarf debris discs
When a star evolves into a white dwarf, the planetary system it hosts can become unstable. Planets in such systems may then be scattered onto star-grazing orbits, leading to their tidal disruption as they pass within the white dwarf's Roche limit. We study the massive, compact debris discs that may arrise from this process using a combination of analytical estimates and numerical modelling. The discs are gravitationally unstable, resulting in an enhanced effective viscosity due to angular momentum transport associated with self-gravity wakes. For disc masses greater than ~1026 g (corresponding to progenitor objects comparable to the Galilean moons), viscous spreading dominates over Poynting-Robertson drag in the outer parts of the disc. In such massive discs, mass is transported both in- and outwards. When the outward-flowing material spreads beyond the Roche limit, it coagulates into new (minor) planets in a process analogous to the ongoing formation of Saturn's innermost moonlets. This process recycles a substantial fraction of the original disc mass (tens of percents), with the bulk of the mass locked in a single large body orbitting in a 2:1 mean-motion resonance with the Roche limit. As such, the recycling of a tidally disrupted super-Earth could yield an Earth-mass planet on a 10--20 hr orbit. For white dwarfs with a temperature below 6000–7000 K (corresponding to a cooling age of >1--2 Gyr), this orbit is located in the white dwarf's habitable zone. The recycling process also creates a string of smaller bodies just outside the Roche limit. These may account for the collection of minor planets postulated to orbit white dwarf WD 1145+017.

Post Main Sequence Planetary System Science, Part 2 (Chair: Michele Bannister)

Alexander Mustill, Lunds Universitet
The dynamics of post-main sequence planetary systems
The study of planetary systems after their host stars have left the main sequence is of fundamental importance for exoplanet science, as the most direct determination of the compositions of extra-Solar planets, asteroids and comets is in fact made by an analysis of the elemental abundances of the remnants of these bodies accreted into the atmospheres of white dwarfs. To understand how the accreted bodies relate to the source populations in the planetary system, and to model their dynamical delivery to the white dwarf, it is necessary to understand the effects of stellar evolution on bodies' orbits. On the red giant branch (RGB) and asymptotic giant branch (AGB) prior to becoming a white dwarf, stars expand to a large size (>1 au) and are easily deformed by orbiting planets, leading to tidal energy dissipation and orbital decay. They also lose half or more of their mass, causing the expansion of bodies' orbits. This mass loss increases the planet:star mass ratio, so planetary systems orbiting white dwarfs can be much less stable than those orbiting their main-sequence progenitors. Finally, small bodies in the system experience strong non-gravitational forces during the RGB and AGB: aerodynamic drag from the mass shed by the star, and strong radiation forces as the stellar luminosity reaches several thousand Solar luminosities. I will review these effects, focusing on planet--star tidal interactions and planet--asteroid interactions, and I will discuss some of the numerical challenges in modelling systems over their entire lifetimes of multiple Gyr.
Uri Malamudl, Technion Israel Institute of Technology
Post main sequence evolution of icy minor planets: water retention and white dwarf pollution
We investigate the evolution of icy minor planets from the moment of their birth and through the all evolutionary stages of their host stars, including the main sequence, red giant branch and asymptotic giant branch phases. We then asses the degree of water retention in planetary systems around white dwarf, as a function of various parameters. We consider progenitor stars of different masses and metallicities. We also consider minor planets of various sizes, initial orbital distances, compositions and formation times. Our results indicate that water can survive to the white dwarf stage in a variety of circumstances, especially around G, F, A and even some B type stars. We discuss the significance of water retention with respect to white dwarf pollution and also for planet habitability.
Matthew Payne, Harvard-Smithsonian CfA
The Evolution of Small Bodies in Exo-Planetary Systems through All Stages of Stellar Evolution
I will review the evolution of exo-planetary systems through all stages of stellar evolution, concentrating on the implications for exo-asteroids, exo-moons and exo-Oort clouds as the central star ages of the main sequence and ultimately becomes a white dwarf. I will discuss recent progress in the field and the related outstanding dynamical questions.
Dimitri Veras, University of Warwick
Simulating the tidal disruption of the asteroid orbiting white dwarf WD 1145+017
Post-main-sequence planetary science has been galvanised by the striking variability, depth and shape of the photometric transit curves due to objects orbiting white dwarf WD 1145+017, a star which also hosts a dusty debris disc and circumstellar gas, and displays strong metal atmospheric pollution. However, the physical properties of the likely asteroid which is discharging disintegrating fragments remain largely unconstrained from the observations. This process has not yet been modelled numerically. Here, we use the N-body code PKDGRAV to compute dissipation properties for asteroids of different spins, densities, masses, and eccentricities. We simulate both homogeneous and differentiated asteroids, for up to two years, and find that the disruption timescale is strongly dependent on density and eccentricity, but weakly dependent on mass and spin. We find that primarily rocky differentiated bodies with

moderate (~3-4 g/cm^3) bulk densities on near-circular (e <~ 0.1) orbits can remain intact while occasionally shedding mass from their mantles. These results suggest that the asteroid orbiting WD 1145+017 is differentiated, resides just outside of the Roche radius for bulk density but just inside the Roche radius for mantle density, and is more akin physically to an asteroid like Vesta instead of one like Itokawa.

Planetary Formation and System Architecture, Part 1 (Chair: Matija Cuk)

Matthew Clement, University of Oklahoma
An Early Instabilities Effect on Terrestrial Planetary Formation
Simulations of terrestrial planet formation are highly successful at reproducing many observed qualities of the solar system, but replicating the small mass of Mars in standard planet formation models has proven difficult. A common assumption made by such studies is that the inner planets form in the presence of a system of giant planets on dynamically stable orbits. The presence of the gas giants, particularly Jupiter and Saturn, is important in shaping the orbits and masses of the terrestrial planets. However, it is widely accepted that the outer planets experienced a period of orbital instability sometime after the disappearance of the gas disk (Tsiganis et al., 2005; Gomes et al., 2005; Levison et al., 2011 and Bottke et al., 2012). Here we ask a simple question: what would happen if such an instability (commonly referred to as the Nice Model) occurred during the giant impact phase of terrestrial planetary formation? Previous works (eg: Brasser et al., 2009 and Angora & Lin, 2012) have analyzed the consequences of a Nice Model instability on the dynamics of fully formed terrestrial planets, and we now present a study of the effect of an early instability on the formation of the terrestrial planets. We show that such a scenario often significantly reduces the mass of Mars analogs. Additionally, our simulations can reproduce many other qualities of the inner solar system used as benchmarks to evaluate previous terrestrial planet formation models such as formation timescales, volatile delivery to Earth, and the depletion of the asteroid belt.
Anne-Sophie Libert, University of Namur
Influence of resonant periodic orbits on the formation of giant planetary systems
The late-stage formation of giant planetary systems leads to interesting dynamical mechanisms. By use of extensive n-body simulations, we follow the evolution of three giant planets in the late stage of the gas disc, investigating the gravitational interactions among the planets during the migration phase. Our simulations, which take into account the Type-II migration, the damping of planetary eccentricity and inclination, and an exponential decrease of the disc mass, reproduce the semi-major axis and eccentricity distributions of the detected giant planets. We show that, starting from quasi-circular and quasi-coplanar orbits, highly mutually inclined systems can form, despite the strong eccentricity and inclination damping, due to planet-planet scattering and/or resonant phenomena. A detailed analysis of the long-term dynamical evolutions of these 3D systems is performed, with a particular emphasis on the different inclination-growth mechanisms. We observe that 30% of the final system architectures are strongly affected by a mean-motion resonance. While inclination-type resonances are commonly observed at large eccentricities, we show here that inclination excitation can also be produced at small to moderate eccentricities. We perform a dynamical study of our results, guided by the computation of vertical critical orbits and the bifurcation of families of spatial periodic orbits.
Kedron Silsbee, Princeton University
Planet formation in binary systems: simulating coagulation using analytically determined collision velocities
The existence of planets in tight binary systems presents an interesting puzzle. It is thought that cores of giant planets form via agglomeration of planetesimals in mutual collisions. However, in tight binary systems, one would naïvely expect the collision velocities between planetesimals to be so high that even 100 km bodies would be destroyed, rather than growing in mutual collisions. In these systems, planetesimals are perturbed by gravity from the companion star, and gravity and gas drag from a massive eccentric gas disk. There is a damaging secular resonance that occurs due to the

combination of disk gravity and gravity from the binary companion, however the disk gravity can also create locations of low relative eccentricity between planetesimals of different sizes that would not exist if the disk gravity were ignored. Because the gas drag acts more strongly on smaller planetesimals, orbital eccentricity and apsidal angle depend on planetesimal size. Consequently, planetesimal collision velocities depend on the sizes of the collision partners. Same-size bodies collide at low velocity because their orbits are apsidally aligned. Therefore, often in a given environment some collisions will lead to planetesimal growth, and some to erosion or destruction. This variety of collisional outcomes makes it difficult to determine whether any planetesimals can grow to large sizes. We run a multi-annulus coagulation/fragmentation simulation that also includes the effect of size-dependent radial drift of planetesimals to determine the minimum size of initial planetesimal necessary for growth to large sizes in collisions. The minimum initial size of planetesimal necessary for growth depends greatly on the disk mass, eccentricity and the degree of apsidal alignment with the binary. We find that in a wide variety of situations, it is a reasonable approximation that growth occurs as long as there are no collisions capable of completely destroying a planetesimal, but erosion by moderately damaging collisions can also prevent growth from occurring.
Craig Agnor, Queen Mary University of London
On the Present and Past Secular Architecture of the Terrestrial Planets
Understanding the origin, stability, and long-term evolution of the solar system is a classic problem in dynamical astronomy. Over time-scales longer than 0.1Myr the orbital evolution of the solar system is primarily driven by secular dynamics (i.e., those related to orbital precession). Indeed, using a linearised model of the solar system, Laplace and Lagrange were able to show that secular variations of the terrestrial planets' eccentricities are bounded and stable from orbit crossing. The secular architecture the terrestrial planets is often described in terms of the eccentricity and inclination amplitudes of the linear eigenmodes or in terms of the system's so-called angular momentum deficit. These quantities are constant in the linear approximation and their values for the observed solar system have been used as constraints on the primordial evolution of the planets, including models of terrestrial planet formation (e.g., Raymond et al. 2009, Jacobson and Morbidelli 2014), giant planet migration (e.g., Brasser et al. 2009, Agnor and Lin 2012) and aspects of the terrestrial late veneer (e.g., Raymond et al. 2013). However, as is well-known, the orbital evolution of the terrestrial planets is not linear and the secular amplitudes change with time. Long-term integrations and analytic arguments have shown the evolution of the inner planets to be chaotic with characteristic lyapunov times of \sim 5 Myr (e.g., Laskar 1989, Batygin & Laughlin 2008). This nonlinear behaviour is driven by the interaction of secular resonances (e.g., Laskar 1990, Lithwick and Wu 2011). The resulting chaotic orbital diffusion of the terrestrial planets may be modest or lead to instability of the system (Laskar 2008). Further, orbital integrations demonstrate that Mercury may evolve to orbit crossing with Venus over the next 5Gyr with a probability of about one percent (Laskar and Gastineau 2009). At the meeting I will present results of new long-term orbital integrations of the solar system and discuss the extent that the observed orbits of the terrestrial planets may be used to constrain their primordial state and early evolution.
Billy Quarles, University of Oklahoma
Maximizing planet packing in the alpha Centauri AB system
Recent observational searches have prompted a rebirth of inquiry surrounding the alpha Centauri AB system. Moreover, numerical studies have suggested that planets can form within dynamically stable zones close to the parent stars. Our previous work (Quarles & Lissauer 2016) determined how individual planets interact with the host binary and the dynamical imprint that arises on billion year timescales. We investigate how the prospects of stability can be altered due to interplanetary interactions within multiple planet systems orbiting either stellar component. We find that systems of tightly packed Earth-mass planets can persist on timescales greater than the age of the binary within each star’s habitable zone. Additionally, the number of planets and the spacing in mutual Hill radii depends on the assumed initial eccentricity due to a forced eccentricity induced by the binary companion.
Christopher Spalding, California Institute of Technology
The Intrinsic Multiplicity of Single-transiting Kepler Systems

Within the Kepler dataset, an over-abundance of single-transiting planetary systems, relative to those exhibiting multiple transits, has been interpreted as evidence for two separate populations. Within the framework of this "Kepler Dichotomy," one population exhibits small mutual inclinations between planetary orbits, facilitating multiple transits to be observed along Kepler's line of sight. Conversely, a second population may either consist of intrinsically single planets, or systems of multiple planets possessing significant mutual inclinations between their orbits. To date, no model has been able to decisively distinguish between these two possibilities. Our recent theoretical work has suggested that the gradual fading of the quadrupole moment of the central star can induce dynamical instabilities soon after disk dispersal within tightly-packed planetary systems, such as Kepler-11. This implies that the single-transits often reflect truly single planets. In this talk, we utilize recent mass measurements of lower-multiplicity Kepler systems in order to determine the generality of this instability mechanism across the range of known planetary systems. Through such an approach we are able to place constraints on whether the observed single transiting planets typically possess unseen companion planets on inclined orbits.

Planetary Formation and System Architecture, Part 2 (Chair: Ann-Marie Madigan)

Nikolaos Georgakarakos, New York University Abu Dhabi
Long term evolution of planetary systems with a terrestrial planet and a giant planet
We study the long term orbital evolution of a terrestrial planet under the gravitational perturbations of a giant planet. In particular, we are interested in situations where the two planets are in the same plane and are relatively close. We examine both possible configurations: the giant planet orbit being either outside or inside the orbit of the smaller planet. The perturbing potential is expanded to high orders and an analytical solution of the terrestrial planetary orbit is derived. The analytical estimates are then compared against results from the numerical integration of the full equations of motion and we find that the analytical solution works reasonably well. An interesting finding is that the new analytical estimates improve greatly the predictions for the timescales of the orbital evolution of the terrestrial planet compared to an octupole order expansion.
Katherine A. Kretke, SSERVI/Southwest Research Institute
Effect of Giant Planet Formation on the Compositional Mixture of the Asteroid Belt
The asteroid belt is observed to be a mixture of objects with different compositions, with volatile-poor asteroids (mostly S-complex) dominant in the inner asteroid belt while volatile-rich (mostly C-complex) asteroids dominate the outer asteroid belt. While this general compositional stratification was originally thought to be an indicator of the primordial temperature gradient in the protoplanetary disk, the very distinct properties of these populations suggest that they must represent two completely decoupled reservoirs, not a simple gradient (e.g., Warren 2011). It is possible to create this general stratification (as well as the observed mixing) as the implantation of outer Solar System material into the asteroid belt by the early migration of the giant planets (e.g. the Grand Tack, Walsh et al. 2011). However, this presupposes that the inner and outer Solar System materials were still sorted in their primordial locations prior to any migration of the planets. The lack of a fully dynamically self-consistent model of giant planet core formation has prevented the study of how the core formation process itself may result in dynamical mixing in the early Solar System's history. Recently, pebble accretion, the process by which planetesimals can grow to giant planet cores via the accretion of small, rapidly drifting sub-meter-sized bodies known as "pebbles," (Lambrechts & Johansen 2012, Levison, Kretke & Duncan 2015) finally offers such a model. Here we show how the process of giant planet formation will impact the surrounding planetesimal population, possibly resulting in the observed compositional mixture of the asteroid belt, without requiring a dramatic migration of the giant planets. For example, preliminary runs suggest planetesimals from the Jupiter-formation zone can be implanted in the outer main belt via interactions with scattered Jupiter-zone protoplanets. This could potentially provide an alternative non-Grand Tack solution to the origin of many C-complex bodies, including Ceres.

The Caledonian Symmetric Four- and Five-Body Problems (Chair: Ann-Marie Madigan)

Bonnie Steves, Glasgow Caledonian University
Analytical stability criteria for the Caledonian Symmetric Four and Five Body Problems
Analytical studies of the stability of three or more body gravitational systems are difficult because of the greater number of variables involved with the increasing number of bodies and the limitation of 10 integrals that exist in the gravitational n-body problem. Utilisation of symmetries or the neglecting of the masses of some of the bodies compared to others can simplify the dynamical problem and enable global analytical stability solutions to be derived. These symmetric and restricted few body systems with their analytical stability criterion can then provide useful information on the stability of the general few body system when near symmetry or the restricted situation. Even with symmetrical reductions, analytical stability derivations for four and five body problems are rare. In this paper, we develop an analytical stability criterion for the Caledonian Symmetric Five Body Problem (CS5BP), a dynamically symmetrical planar problem with two pairs of equal masses and a fifth mass located at the centre of mass. Sundman's inequality is applied to derive boundary surfaces to the allowed real motion of the system. This enables the derivation of a stability criterion valid for all time for the hierarchical stability of the CS5BP and its subset the Caledonian Symmetric Four Body Problem (CSFBP), where the central mass is taken to be equal to zero. We show that the hierarchical stability depends solely on the Szebehely constant C0, which is a function of the total energy H and angular momentum c. The critical value Ccrit at which the system becomes hierarchically stable for all time depends only on the two mass ratios of the symmetric five body system. We then explore the effect on the stability of the whole system of adding an increasing massive central body. It is shown both analytically and numerically that all CS5BPs and CSFBPs of different mass ratios are hierarchically stable if C0 > 0.0659 and C0 > 0.0465, respectively. The Caledonian Symmetric Four and Five Body gravitational models are relevant to the study of the stability and evolution of symmetric quadruple/quintuple stellar clusters and symmetric exoplanetary systems of two planets orbiting a binary/triplet of stars.
Alex Davis, University of Colorado at Boulder
Constraining Binary Asteroid Mass Distributions Based On Mutual Dynamics (Duncombe Award winner)
The mutual gravitational potential and torques of binary asteroid systems results in a complex coupling of attitude and orbital motion based on the mass distribution of each body. For a doubly-synchronous binary system observations of the mutual motion can be leveraged to identify and measure the unique mass distributions of each body. By implementing arbitrary shape and order computation of the full two-body problem (F2BP) equilibria we study the influence of asteroid asymmetries on separation and orientation of a doubly-synchronous system. Additionally, simulations of binary systems perturbed from doubly-synchronous behavior are studied to understand the effects of mass distribution perturbations on precession and nutation rates such that unique behaviors can be isolated and used to measure asteroid mass distributions. We apply our investigation to the Trojan binary asteroid system 617 Patroclus and Menoetius (1906 VY), which will be the final flyby target of the recently announced LUCY Discovery mission in March 2033. This binary asteroid system is of particular interest due to the results of a recent stellar occultation study (DPS 46, id.506.09) that suggests the system to be doubly-synchronous and consisting of two-similarly sized oblate ellipsoids, in addition to suggesting the presence mass asymmetries resulting from an impact crater on the southern limb of Menoetius.

Iapetus! (Chair: Ann-Marie Madigan)

Matija Cuk, SETI Institute
A Secular Resonance Between Iapetus and the Giant Planets

Iapetus is the outermost of the regular satellites of Saturn, and its origin and evolution present a number of unsolved problems. From the point of view of orbital dynamics, it is remarkable that Iapetus has a large inclination (8 degrees) and a significantly smaller eccentricity (0.03), contrary to the pattern expected if its orbit was excited by encounters between Saturn and other planets early in the Solar System's history (Nesvorny et al, 2014). Here we report our long-term numerical integrations of Iapetus's orbit that show multi-Myr oscillations of Iapetus's eccentricity with an amplitude on the order of 0.01. We find that the basic argument causing this behavior is the sum of the longitude of pericenter and the longitude of the node of Iapetus, with a 0.3 Myr period. This argument appears to be in resonance with the period of the g5 mode in the eccentricity and perihelion of Saturn. We find that our nominal solution, including Saturn's oblateness, Titan, Iapetus and all four giant planets, shows librations of the argument: \varpi_Iapetus - \varpi_g5 + \Omega_Iapetus - \Omega_SaturnEq, where \varpi and \Omega are the longitudes of pericenters and nodes, respectively, and \Omega_SaturnEq is Saturn's equinox. While planetary perturbations are crucial in generating the g5 mode and therefore maintaining this resonance, we find that Iapetus is affected by the planets only indirectly, with the Sun being the dominant direct perturber. The libration is stable for tens of Myr for the nominal rate of Saturn's pole precession (French et al, 2017), and appears stable indefinitely if we assume a secular resonance between Saturn's node and the secular mode g18 (Ward and Hamilton, 2004; Hamilton and Ward, 2004). We will present the implication of this resonance for the origin of Iapetus's orbit and the dynamical history of Saturn's system. This research is funded by NASA Outer Planets Research Program award NNX14AO38G. References: French, R. G., McGhee-French, C. A., Lonergan, K., et al. 2017, Icarus, 290, 14; Hamilton, D. P., & Ward, W. R. 2004, AJ, 128, 2510; Nesvorny, D., Vokrouhlicky, D., Deienno, R., & Walsh, K. J. 2014, AJ, 148, 52; Ward, W. R., & Hamilton, D. P. 2004, AJ, 128, 2501.

William Polycarpe, Observatoire de Paris

Is Titan responsible for Iapetus' orbit?

Latest astrometrical results on Saturnian moons show evidence for high migration rates (Lainey et al. 2012; 2016). The tidal dissipation in the planet is responsible for those large orbital expansions and should therefore be much stronger than usually expected. The idea of significant tidal dissipation in the massive core (Remus et al. 2012) and the convective envelope (Le Guenel et al. 2015; Fuller et al. 2016) of the planet has been brought forward as a likely explanation. Nevertheless, high changes in semi-major axes of the moons shuffle up the ideas we had on the past evolution of the system of Saturn. In particular, depending on tidal mechanisms at play, several Mean Motion Resonances could have been crossed just a few million years ago. In the frame of high tidal migration, we investigate the consequences of the past 5:1 mean motion resonance between Titan and Iapetus, which could have happened between 5 and 500 million years ago. Numerical simulations show that the most common outcome for Iapetus is to be ejected, as Titan migrates through the resonance. However, if Titan has a very high recession (Q <2000), Iapetus may survive the resonance and come out of it with an eccentricity consistent with today's value. The effect on Iapetus' inclination is still under investigation.

Tuesday, June 13

Impact of Gaia Astrometry on Dynamical Astronomy, Part 1 (Chair: Monica Valluri)

Daniel Hestroffer, Paris Observatory

Astrometry and dynamics of Solar System Objects with Gaia GDR observations and catalogues

The Gaia ESA space mission has started to provide its harvest with the first Gaia data release DR1, published in September 2016. Gaia DR1 provides positions for about 1

billion stars and proper motion for the Tycho-Gaia TGAS of 2 million stars with unprecedented accuracy. The second data release DR2 will be the major step in the Gaia mission, providing all astrometric parameters (including parallax and proper motion) for a billion stars, in an absolute reference frame - to become the optical ICRF. Gaia DR2 will also provide epoch astrometry for about 13,000 asteroids from its direct observations, down to magnitude V≈20.7. We will discuss the improvement brought by Gaia over 5 years of nominal mission, starting with DR1, and focusing especially on the dynamics of asteroids and other Solar System Objects. This includes use of the catalogue for calibrating future and past photometric and astrometric observations (in particular new reduction of ancient photographic plates digitalised by the NAROO programme), new perspectives for orbit determination and stellar occultations, detection of small acceleration or perturbations for the asteroids. Also we illustrate the ground-based activity coordinated by the Gaia-FUN-SSO network for follow-up observations of newly discovered Near Earth Object.

Todd Henry, RECONS

Our View of the Solar Neighborhood Before, During, and After Gaia

The nearest stars and their companions provide the fundamental framework upon which all of stellar astronomy is based, for individual stars, stellar multiples, and entire stellar populations. We live in exciting times, as our map of the Sun's neighbors becomes enriched with details of other solar systems that will ultimately play key roles in our search for life elsewhere. Gaia will be pivotal in identifying the nearest one million stars that will be targeted for both astrophysical and astrobiological research. In this talk we will discuss the status of nearby star samples, with particular attention paid to the hundreds of stars nearer than 10 parsecs that form a rather well-characterized sample, and the considerable impact of Gaia on the thousands of stars to be found within 25 parsecs. We will also outline a new project carried out by the REsearch Consortium On Nearby Stars (RECONS, www.recons.org [1]) Team focused on K dwarfs within 50 parsecs, in what turns out to be an elegant application of Gaia's DR1 results. There is no doubt that Gaia will enhance our understanding of the nearest stars, with the greatest impact likely to be advancing our appreciation of the Galaxy's most overlooked members, the red dwarfs. This effort has been supported by the NSF through grants AST-0908402, AST-1109445, AST-1412026, and AST-1517413, and via observations made possible by the SMARTS Consortium.

Norbert Zacharias, U.S. Naval Observatory

Galactic Dynamics: new proper motions from Gaia and UCAC

With the Gaia DR1 we now have proper motions accurate on the 0.1 mas/yr level for about 100,000 Hipparcos stars. The Tycho-Gaia astrometric solution (TGAS) furthermore provides proper motions of about 2 million stars on the 1 to 2 mas/yr level. Using TGAS as reference star catalog, the USNO CCD Astrograph Catalog (UCAC) observations were re-reduced and their about epoch 2001 positions combined with Gaia DR1 to obtain proper motions of over 100 millions stars to about magnitude R=16.5 with a proper motion accuracy of 1 to 5 mas/yr (depending on brightness). This UCAC5 data largely extends the TGAS data for galactic dynamics studies, and thus provides a preview of some more exciting science which will be enabled with the Gaia DR2 in April 2018, when accurate proper motions will become available for a billion stars.

Impact of Gaia Astrometry on Dynamical Astronomy, Part 2 (Chair: Norbert Zacharias)

Anna Lisa Varri, University of Edinburgh

New science from the phase space of old stellar systems

Our traditional interpretative picture of the internal dynamics of globular clusters has been recently revolutionized by a series of discoveries about their chemical, structural, and kinematic properties. The empirical evidence that their velocity space is much more complex than usually expected encourages us to use them as refreshingly novel phase space laboratories for some long-forgotten aspects of collisional gravitational dynamics. Such a realization, coupled with the discovery that the stars in clusters were not all born at once in a single population, makes them new, challenging chemodynamical puzzles.

Thanks to the proper motions of thousands of stars that will be available from the Gaia mission, we are about to enter a new "golden age" for the study of the dynamics of this class of stellar systems, as the full phase space of several Galactic globular clusters will be soon unlocked for the first time. In this context, I will present the highlights of a more realistic dynamical paradigm for these intriguing stellar systems, with emphasis on the role of angular momentum, velocity anisotropy and external tidal field. Such a fundamental understanding of the emerging phase space complexity of globulars will allow us to address many open questions about their rich dynamical evolution, their elusive stellar populations and putative black holes, and their role within the history of our Galaxy.

Laura Watkins, Space Telescope Science Institute

Tycho-Gaia Astrometric Solution parallaxes and proper motions for 5 Galactic globular clusters

The Tycho-Gaia Astrometric Solution (TGAS) catalogue from Gaia Data Release 1 provided proper motions (PMs) and parallax estimates for over 2 million stars in the Tycho2 catalogue. Although this catalogue provides PMs for only a very small fraction of stars, compared with the expected catalogues from later data releases, already TGAS has been used to study parallaxes and PMs for a variety of objects in the Local Group. I will present results from our recent pilot in which we searched the TGAS catalogue for stars in Galactic globular clusters (GCs). We identified a total of 20 member stars across 5 GCs — NGC 104 (47 Tucanae), NGC 5272 (M3), NGC 6121 (M4), NGC 6397, and NGC 6656 (M22) — and used them to estimate parallaxes (and hence distances) to the clusters, along with their global proper motions. Combined with literature line-of-sight velocities, we also calculated full space motions for the clusters. I will outline the membership selection process and discuss the subsequent space-motion analysis. I will also compare our PM results to both previous Hubble Space Telescope and ground-based estimates. Our Gaia results compare very well, and highlight the amazing potential of future Gaia data releases.

Monica Valluri, University of Michigan

Using tidal streams to investigate the rotation of the Milky Way's dark matter halo

The dark matter halos surrounding Milky Way like galaxies that are formed in cosmological simulations are triaxial. These simulated triaxial halos are expected to be slowly rotating with log-normal distribution of pattern speeds centered on ~0.148h km/s/kpc (Bailin & Steinmetz 2004, ApJ., 616, 27). Stellar streams arising from a satellite expering tidal disruption inside a slowly rotating triaxial potential are subject to additional forces (e.g., Coriolis forces) that affect the structure of tidal streams. Using the Python Galaxy dynamics package Gala (Price-Whelan, http://gala.adrian.pw [2]) we have generated simulations of tidal streams in a range of triaxial potentials to explore how the structure of Milky Way's tidal streams, especiallly the structure of stream bifurcations and the stream orbital plane, are altered by figure rotation of the triaxial dark matter halo. We investigate what can be infered about halo rotation from current and future data including proper-motions from Gaia. This work is supported by NASA-ATP award NNX15AK79G to the University of Michigan.

Planet and Satellite Rotation and Orientation (Chair: Benoit Noyelles)

Rose-Marie Baland, Royal Observatory of Belgium

The influence of tides and of the precession of the pericenter on the orientation of the rotation axis of a solid Mercury

Mercury's spin axis nearly occupies the Cassini state 1, in which the orbit normal and spin axis precess together with a long period of about 300 000 years. Mercury slightly deviates from that state which is defined for a uniformly precessing rigid planet. Variations in obliquity and deviation from the coplanarity between the spin axis, the normal to the orbit and the normal to the Laplace plane are induced by the slow precession of the pericenter. Moreover, the short-periodic tidal deformations induce a constant shift over time in mean obliquity and deviation, characterized by the tidal love number k2 and by the ratio k2/Q of the tidal Love number over the tidal quality factor, respectively. Including theses effects, we analytically develop a new Cassini state model

and reinterpret recent determination of Mercury's orientation in terms of parameters of Mercury's interior. We also show explicitly that Peale's equation is sometimes wrongly cited in the literature, resulting in wrong estimates of the polar moment of inertia. From the orientation of Stark et al. (2015, Planetary and Space Science, Vol. 117), we find C/MR2=0.3433+/-0.0134, which is 0.9% smaller than the estimate by Stark et al. (2015) themselves, because of our refinements of the Cassini state model (0.1%) and their wrong use of Peale's equation (0.8%). That difference is below the actual precision (3-4%) on the polar moment of inertia but may be of the order of precision that can be reached with BepiColombo mission (<0.3%). Given the actual precision on the spin axis orientation, we place an upper limit of about 0.02 on the ratio k2/Q and of about 350 on Q (assuming k2=0.5) at the 1 sigma level. The parameter k2 cannot be estimated from the spin axis orientation, because of its correlation with the polar moment of inertia. In the future, the relative precision on the determination of k2/Q from the spin axis orientation could be as good as 30% with BepiColombo, so that the non-elastic parameter of Mercury could be estimated for the first time.

Xiaojin XI, l'Observatoire de Paris

Analytical representation for ephemeris with short time-span - Aplication to the longitude of Titan

Ephemerides of the natural satellites are generally presented in the form of tables, or computed on line, for example like some best ones from JPL or IMCCE. In the sense of fitted the more recent and best observations, analytical representation is not so sufficient, although these representations are valid over a very long time-span. But in some analytical studies, it could be benefitted to have the both advantages. We present here the case of the study of the rotation of Titan, in which we need a representation of the true longitude of Titan. Frequency analysis can be used partially on the numerical ephemerides because of limited time-span. To complete it, we use the form of the analytical representation to obtained their numerical parameters.The method is presented and some results are given.

Marie Yseboodt, Royal Observatory of Belgium

Mars rotation using geodesy data

The position of a Martian lander with respect to the Earth is affected by different aspects of Mars' rotational motions: the nutations, the precession, the length-of-day variations and the polar motion. We derive first-order formulations of the signature of these rotation parameters in the Doppler and range observables between the Earth and a lander on Mars' surface. These expressions are modulated by the diurnal rotation of Mars and they are functions of the lander position. Additionally, the nutation signature in the Doppler observable is proportional to the Earth declination with respect to Mars. The correlations between a pair of rotation parameters can be derived. We also present a comparison of different series of rigid nutation for Mars and how this changes the Doppler signatures. Knowing the correlations between these signatures and the moments when these signatures are not null during one day or on a longer timescale is important to identify strategies that maximize the geophysical return of observations with a geodesy experiment, in particular for the ones on-board the future NASA InSight or ESA-Roscosmos ExoMars2020 missions.

Gwenaël Boué, UPMC

On Titan's obliquity

The Cassini-Huygens mission brings us many valuable information about Saturn's moon Titan, but some of them seem to be incompatible. Measurements of the gravity field coefficients J2 and C22 suggest that its shape is hydrostatic and observations of its rotation state show that it is likely to be in a Cassini state with an obliquity of 0.32 deg. Titan cannot be fully rigid otherwise its equilibrium obliquity would only be one third of the observed value. This agrees with several hints indicating that it possesses a global underneath ocean surrounded by a thin ice shell. But, thus far three layer models are unable to explain Titan's large obliquity assuming both an hydrostatic shape and the absence of significant resonant amplifications. Nevertheless, these models neglect the rotation of the ocean which might play a significant role in the dynamics of Titan's spin pole. Here we revisit the rotation dynamics of a three layered body with a subsurface ocean using a suitable non-canonical Hamiltonian formalism. The system has 7 degrees of freedom, six of which being equally shared by the rigid interior and the shell, and the last

one being due to the rotation of the ocean. We show that this model is able to reconcile the three observations listed above.

Aswin Sekhar, Centre for Earth Evolution and Dynamics

Rapid Enhancement in General Relativistic Precession Rates due to Kozai Mechanism in Solar System Bodies

Two well known phenomena in orbital dynamics associated with low perihelion distance bodies are general relativistic (GR) precession and Lidov-Kozai (LK) oscillations. In this work, we are interested to identify bodies evolving in the near future (i.e. thousands of years in this case) into rapid sungrazing and sun colliding phases and undergoing inclination flips, due to LK like oscillations and being GR active at the same time. We find that LK mechanism leads to secular lowering of perihelion distance which in turn leads to a huge increase in GR precession of the argument of pericentre depending on the initial orbital elements. This in turn gives feedback to the LK mechanism as the eccentricity, inclination and argument of pericentre in Kozai cycles are closely correlated. In this work, we find real examples of solar system bodies which show rapid enhancement in GR precession rates due to LK like oscillations and there are cases where GR precession rate peaks to about 60 times that of the GR precession of Mercury thus showing the strength and complementary nature between these two dynamical phenomena. An analytical treatment is done on few bodies to understand the difference in their orbital evolution in the context of LK mechanism with and without GR precession term by incorporating suitable Hamiltonian dynamics. This result is subsequently matched using numerical integrations to find direct correlations. Real solar system bodies showing both GR precession and LK like oscillations are identified using compiled observational records from IAU-Minor Planet Center, Cometary Catalogue, IAU-Meteor Data Center and performing analytical plus numerical tests on them. This intermediate state (where GR and LK effects are comparable and co-exist) brings up the interesting possibility of drastic changes in GR precession rates during orbital evolution due to sungrazing and sun colliding phases induced by the LK like mechanism, thus combining both these important effects in a unique and dynamically interesting way. Both these phenomena complementing and co-existing at the same time has interesting implications in the long term impact studies of small bodies in general.

Tides and Binaries (Chair: Laura Watkins)

Michelle Vick, Cornell University

Dynamical Tides in Highly Eccentric Binaries: Chaos, Dissipation and Quasi-Steady State (Duncombe Award winner)

Highly eccentric binary systems appear in a variety of astrophysical contexts, ranging from tidal capture in dense star clusters, precursors of tidal disruption events, to high-eccentricity planet migration. In a highly eccentric binary, the tidal potential of one body can excite oscillatory modes in the other during a pericenter passage, resulting in energy exchange between the modes and the binary orbit. The energy in these modes exhibits one of three behaviors over multiple passages: low-amplitude oscillations, large amplitude oscillations corresponding to a resonance between the orbital frequency and the mode frequency, and stochastic growth. We extend previous studies of these phenomena by fully exploring how mode energy evolution depends on the pericenter distance and other parameters. In addition, we consider the effect of linear mode damping on the long-term evolution of the system. We find that the inclusion of damping results in a quasi-steady-state mode energy, even in systems where the mode amplitude would grow stochastically in the absence of dissipation. Lastly, we use MESA-generated stellar models to determine the combination of orbital and stellar parameters that would lead to the three types of mode evolution in a moderately massive star and characterize the magnitude of tidal heating for each regime.

Alexandre Correia, University of Aveiro

Tidal evolution of circumbinary systems

We investigate the secular dynamics of three-body circumbinary systems under the effect of tides. We use the octupolar non-restricted approximation for the orbital interactions, general relativity corrections, the quadrupolar approximation for the spins,

and the viscous linear model for tides. We derive the averaged equations of motion in a simplified vectorial formalism, which is suitable to model the long-term evolution of a wide variety of circumbinary systems in very eccentric and inclined orbits. We show that circumbinary planets with initial arbitrary orbital inclination can become coplanar through a secular resonance between the precession of the orbit and the precession of the spin of one of the stars. We also show that circumbinary systems for which the pericenter of the inner orbit is initially in libration present chaotic motion for the spins and for the eccentricity of the outer orbit.

Wm. Van Altena, Yale University
Sixteen Years of Speckle Interferometry at the WIYN Observatory
Speckle interferometry at Yale started in 1994 with a three-year program of observations at the Yale Southern Observatory at El Leoncito, Argentina. After this experience, we began a long-term program of speckle observations at the WIYN 3.5-m telescope at Kitt Peak National Observatory, first using a MAMA detector, then CCD and finally EMCCD technology. We describe the evolution of the program, its main results in terms of discovered components, orbital parameters and masses. While the Yale program ended in 2013, it provided the springboard for continued speckle efforts at WIYN, the Discovery Channel 4.3-m Telescope, and the Gemini 8.1-m Telescopes for binary star research, exoplanet science, and other projects. An important outcome of this research will be the incorporation of the soon to be released high-precision Gaia parallaxes into our observations.

James Cho, Queen Mary University of London
Turbulent Mixing on Close-In Planets by Libration Tide
A series of high-resolution, pseudospectral simulations of close-in extrasolar planet atmospheres are carried out. This study directly couples accurate fluid dynamics and orbital dynamics. The focus is on robustly capturing the global, nonlinear mixing and redistribution of passive tracers — such as clouds, aerosols, and chemical species — due to libration tide. Modifications of the traditional fluids equations and algorithms are discussed, as well as the role of the background mean-flow. The study shows that the mixing is enhanced and is much more complex, compared with the simple diffusion and advection reported in previous studies without the inclusion of tidal forcing.

Brouwer Award Lecture (Chair: Craig Agnor)

Rosemary Wyse, Johns Hopkins University
Brouwer Award Lecture: The Cosmological Context of the Milky Way Galaxy
I will describe some recent work using the Milky Way and its satellite galaxies to invevstigate how disc galaxies form and evolve. I will discuss how the combination of large observational datasets of stellar positions, parallaxes, kinematics and chemical abundances with high-resolution simulations has provided unprecedented opportunities and new insights.

Wednesday, June 14

Kuiper Belt and Planet Nine (Chair: Matthew Payne)

Michele Bannister, Queen's University Belfast
Fantastic Icy Worlds and Where to Find Them
The outer Solar System has a wealth of recent discoveries that inform our understanding of orbital dynamics and provoke exciting new questions. The populations of small icy worlds orbiting in the vast volume beyond Neptune are remarkably abundant. Observational surveys including the Outer Solar System Origins Survey are revealing an intricate filigree of mean-motion resonant orbits, emplaced by the historic migration of

Neptune. There are also new discoveries of rare trans-Neptunian objects that orbit even further afield, so far from planetary and Galactic tide influences that they are not thought to be produced in the current known planetary architecture of the Solar System. These have informed the recent debate on the existence of a distant giant planet. The hard-to-observe extreme TNOs require a formation method - and offer tantalizing hints that our Solar System is more complex than our current conception.

Rodney Gomes, Obs. Nacional

Making the cold Kuiper belt in a planetary instability migration model

Numerical integrations of the equations of motion of Jupiter, Saturn, three ice cores and a disk of planetesimals are undertaken. Two of the ice planets stand for Uranus and Neptune and a third one is expected to be ejected from the solar system. The planets start in compact cold orbits and each one is in mean motion resonance with its neighbor(s). The disk of planetesimals is placed just outside the outermost planet and is extended to 45 au. Five hundred integrations are done for each of four masses assigned to the disk, which are 25, 30, 35 and 40 Earth masses. The integrations are extended to 100 My. After that, I choose the successful runs in which there are four planets left in closed orbits around the Sun and I separate the good runs among the successful ones, defined by semi-major axes ranges around and not too far from the real ones. Among these good runs, I further choose by visual inspection those that yield an orbital distribution of planetesimals at the Kuiper belt region that resembles the real cold Kuiper belt. I extend these runs to 1 Gy and, after that, to 4.5 Gy. These last integrations for 3.5 Gy are done after replacing the orbits of the planets in the end of the 1 Gy integrations by their current orbits, changing the semi-major axes of the planetesimals so as to keep the same mean motion ratio with Neptune and assigning null masses for the planetesimals. Orbital distributions of the cold Kuiper belt obtained in some of the runs at 4.5 Gy are quite similar to that of the real cold Kuiper belt. The mass in the Kuiper belt region can be dynamically eroded to up to 90% of the original mass. The main conclusion is that the cold Kuiper belt is compatible with a past planetary instability phase even though in some of these runs Neptune's semi-major axis and eccentricity attained values simultaneously larger than 20 au and 0.2 for over 1 My.

Darin Ragozzine, Brigham Young University

Tripling the Haumea Family Membership to Constrain Its Formation

At DDA 2007, I discussed the newly discovered collisional/dynamical family of the dwarf planet Haumea in the outer solar system. With only 8 Haumea family members at that time, characterization was limited but consistent with a surprisingly concentrated distribution of family members. In particular, the dynamical distance (Delta v) to the furthest family members was only ~150 m/s, a far cry from the expected ~1000 m/s (Haumea's escape velocity) in a catastrophic collision. Since 2007, this unusual concentration of family members has been observationally and dynamically strengthened and has prompted new hypotheses. Two examples of Haumea formation hypotheses are the graze and merge model from Leinhardt et al. 2010 and the satellite destruction model of Schlichting & Sari 2009 (preferred by Cuk et al. 2013 for the formation of Haumea's two satellites). These models predict very different distributions of family members which can now be tested. Using the discovery of new KBOs in the last ten years, we have ~tripled the number of dynamically identified Haumea family members. We will report on the comparison of the distribution of these family members in light of the competing hypotheses and discuss implications for the formation of Haumea.

Elizabeth Bailey, Caltech

The Role of Resonances in the Search for Planet Nine

It has recently been noted that a population of distant Kuiper belt objects with semimajor axis greater than approximately 150 au exhibits a surprising degree of clustering in longitude of perihelion and ascending node. This clustering, along with numerous other phenomena in the solar system, can be explained by the existence of a massive, eccentric planet residing well beyond the orbit of Neptune. Moreover, it has been proposed that resonant interaction between Planet Nine and distant, confined objects may inform the present-day semimajor axis and location of Planet Nine along its orbit, if the resonances at play can be identified. Inspired by this notion, we have carried out a suite of numerical simulations aimed at characterizing capture probabilities of Planet Nine mean-motion resonances, and have found that numerous high-order resonances

successfully trap Kuiper belt objects, precluding a simple identification of the dominant commensurability. At the same time, our simulations show that resonant relationships are indeed key to maintaining long-term stability of confined KBOs, and breaking the resonant lock results in the rapid onset of dynamical instabilities within the distant Kuiper Belt.

Robert Jacobson, JPL

Constraints on the Mass and Location of Planet 9 set by Range and VLBI Observations of Spacecraft at Saturn

Batygin and Brown, 2016 AJ, found that all Kuiper belt objects (KBOs) with well determined orbits having periods greater than 4000 years share nearly the same orbital plane and are apsidally aligned. They attribute this orbital clustering to the existence of a distant planet, Planet 9, well beyond Neptune, with a mass roughly ten times that of Earth. If such a planet exists, it would affect the motion of the known solar system planets, in particular Saturn, which is well observed with radiometric ranging from the Voyager and Cassini spacecraft and VLBI observations of Cassini. The current planetary ephemerides do not account for the postulated Planet 9, yet their fit to the observational data shows no obvious effect that could be attributed to neglecting that planet. However, it is possible that the effect could be absorbed by the estimated parameters used to determine the ephemerides. Those parameters include the planetary orbital elements, mass of the Sun, and the masses of the asteroids that perturb the Martian orbit. We recently updated the Voyager and Cassini data sets and extended the latter through 2017 March. We analyze the sensitivity of these data to the tidal perturbations caused by Planet 9 for a range of positions on the sky and tidal parameters (the ratio of the mass of Planet 9 to the cube of its distance from Saturn). We determine an upper bound on the tidal parameter and the most probable directions consistent with the observational data.

Comets (Chair: Phil Nicholson)

Travis Swenson, Stanford University

Invariant Manifolds and the Transport and Capture of Comet Shoemaker-Levy 9

Poincaré stated that “periodic orbits” are the only means by which we can understand the dynamics of differential equations. The objects he really meant are the “invariant manifolds of periodic orbits” which he discovered. It was the intersection of invariant manifolds that led to his discovery of homoclinic orbits and deterministic chaos in his celebrated work on the 3 body problem. Koon, Lo, Marsden, Ross 2000 explained the theory of how invariant manifolds of periodic orbits around the L1 and L2 Lagrange points control the transport of small bodies between the 2:3 resonance outside of Jupiter’s orbit to the 3:2 resonance inside of Jupiter’s orbit. This resonance transition is exhibited by many members of the Jupiter Family of comets as shown by Howell, Marchand, and Lo 2001 computed in the JPL ephemeris model. These comets include Gehrels 3, Helin-Roman-Crockett, Oterma, and others. We present some recent work on the role of invariant manifolds for the capture and impact of comet Shoemaker-Levy9 (SL9). The comet underwent resonance transition in the Sun-Saturn three-body problem until it was captured by invariant manifolds of the Sun-Jupiter three-body problem. We show how these manifolds guided SL9 towards Jupiter and through the periodic orbits which act as gateways to Jupiter and the inner solar system. We demonstrate that invariant manifolds controlled the dynamics of capture, ultimately leading to the impact of SL9 in 1994.

Luke Dones, Southwest Research Institute

Ways of Changing the Number and Size Distribution of Ecliptic Comets

The existence of the Kuiper Belt was proposed because of the need for a low-inclination source for the Jupiter-family comets (JFCs). Indeed, the Kuiper Belt is thought to be the main reservoir of ecliptic comets (ECs), which include the JFCs and Centaurs. Ironically, we still do not know whether the belt, specifically its Scattered Disk, provides an adequate source for the ECs (Volk and Malhotra 2008). ECs are also thought to be the main source of Sun-orbiting impactors on the regular moons of the giant planets (Zahnle et al. 2003 [Z03]). Some models of the cometary orbital distribution used by Z03 and others to estimate impact rates assume comets are indestructible; in fact, many

cometssplit, sometimes far from the Sun (Fernández 2009). Assuming shatterproof comets may lead to incorrect results for cometary orbital distributions. Other models impose a physical lifetime for bodies that approach within ~3 AU of the Sun, where sublimation of water ice begins, after which a comet is assumed to be dormant or disrupted (Nesvorný et al. 2017). In reality, some comets (e.g., 29P, Hale-Bopp) are active due to volatiles such as CO and CO2 beyond the orbit of Jupiter (Womack et al. 2017). 174P/Echeclus underwent a 7-magnitude outburst 13 AU from the Sun (Rousselot et al. 2016), and CO emission was recently detected from Echeclus at 6 AU (Wierzchos et al. 2017). We will estimate the effects of several mechanisms on the number and size distribution of comet nuclei as a function of distance from the Sun, including cometary activity and spontaneous disruption; tidal disruption by a giant planet, as happened for Shoemaker-Levy 9; and tidal disruption of binaries, which are numerous among "cold classical" Kuiper Belt Objects (Fraser et al. 2017). **We thank the Cassini Data Analysis Program for support.** **Fernández Y (2009). Planet. Space. Sci. 57, 1218. Fraser WC, et al. (2017). Nat. Astron. 1, 0088. Nesvorný D, et al. (2017). In preparation. Rousselot P, et al. (2016). MNRAS 462, S432. Volk K, Malhotra R (2008). Astrophys. J. 687, 714. Wierzchos K, Womack M, Sarid G. (2017). Astron. J., in press. Womack M, Sarid G, Wierzchos, K (2017). Publ. Astron. Soc. Pac. 129, 031001. Zahnle K, et al. (2003). Icarus 163, 263.**

Rings and Moons Beyond Saturn (Chair: Phil Nicholson)

Robert Chancia, University of Idaho
Weighing Uranus' moon Cressida with the η ring (Duncombe Award winner)
The η ring is one of the narrow rings of Uranus, consisting of a dense core that is 1-2 km wide and a diffuse outer sheet spanning about 40 km. Its dense core lies just exterior to the 3:2 Inner Lindblad Resonance of the small moon Cressida. We fit the η ring radius residuals and longitudes from a complete set of both ground-based and Voyager stellar and radio occultations of the Uranian rings spanning 1977-2002. We find variations in the radial position of the η ring that are likely generated by this resonance, and take the form of a 3-lobed structure rotating at an angular rate equal to the mean motion of the moon Cressida. The ring radially oscillates with an amplitude of ~0.7 km, which is consistent with the expected shape due to the perturbations from this moon. The magnitude of these variations provides the first measurement of the mass of the moon Cressida or, indeed, any of Uranus' small inner moons. A better grasp of the inner Uranian satellites' masses will provide another clue to the composition, dynamical stability, and history of this tightly packed system of moons.
Bruno Sicardy, Obs. Paris and Paris 6 Univ.
The dynamics of rings around small, irregular bodies
Stellar occultations revealed the presence of two dense rings around the Centaur object (10199) Chariklo (Braga-Ribas et al., Nature 508, 72, 2014). This is the first ring system discovered around an object that is not a giant planet, suggesting that rings may exist around numerous bodies in the solar system. Chariklo's rings roughly reside at the outer limit of the Roche zone of the body. Moreover, the main ring has sharp edges, which call for the presence of putative shepherd satellites. Those characteristics give an image of Chariklo's rings that are rather similar, in terms of dynamics, to those surrounding the gaseous planets. An important difference exists, however, between giant planets and small bodies: the formers are highly axisymmetric, while the latters can support mass anomalies (eg surface topographic features) or non-spherical shapes (eg an ellipsoidal figure of equilibrium) that involve masses, relative to the body itself, as large as 10-4-10-3. We investigate the effect of non-axisymmetric terms in the potential of the body upon a collisional debris disk that initially surrounds a small irregular body. We show that the corotation points being maxima of energy, dissipative collisions remove the particles from the corotation zone over short time scales (< 106 years). Moreover, the Lindblad resonances inside the corotation radius create torques that drive the particles onto the surface of the central body. Conversely, the outer Lindblad resonances push the disk material beyond the outer 3/2 and 2/1 Lindblad resonances. Taking as an example Chariklo's ring system, for which recent data have been obtained from stellar occultations, we show that the Lindblad resonant torques actuate over short time scales

(< 106 years). This general picture offers a natural explanation of the presence of dense rings at the outer limit of Chariklo's Roche zone, and their absence closer to the body.
The work leading to this results has received funding from the European Research Council under the European Community's H2020 2014-2020 ERC grant Agreement n°669416 "Lucky Star".
Mark Showalter, SETI Institute
Ongoing Dynamics and Evolution of Neptune's Ring-Moon System
We report results derived from observations of the Neptune system using the Hubble Space Telescope (HST) during August 2016. These observations entail repeated, extremely long exposures through the broadest available filter on the WFC3/UVIS instrument to reveal details of Neptune's faint rings and small, inner moons. The work complements similar observations performed by HST in 2004-2005 and 2009. A principal goal was the recovery of the small moon S/2004 N 1 (henceforth N14), which was first reported in 2009. New images show the moon clearly and make it possible to obtain accurate orbital elements for the first time. A complete analysis of all data 2004-2016 reveals that the mean motion n = 378.90616 +/- 0.00003 degrees per day, corresponding to a semimajor axis a = 105,283 km. Eccentricity and inclination are quite small, with e < 0.001 and i < 0.1 degrees. (This result accounts for the local Laplace Plane tilt of ~ 0.4 degrees). N14 has a physical radius R = 13-15 km, assuming its albedo is 0.09 +/- 0.01, which is the range of Neptune's other inner moons. It orbits interior to the much larger moon Proteus (a = 117,647 km; R = 210 km). Tides are believed to have caused Proteus to spiral outward significantly since its origin, and we find that N14 orbits within the radial zone likely crossed by Proteus. We suggest that N14 may have originated as debris ejected from an impact into Proteus; Proteus subsequently continued to evolve outward but the debris accreted into N14 and remains at its original point of origin. Naiad, the innermost of Neptune's moons, is now orbiting ~ 120 degrees ahead of its published orbital elements. This represents only a 1-sigma correction from its mean motion as derived from Voyager data, but it indicates that later, purported detections of Naiad with the Keck telescope were almost certainly misidentifications. The arcs in the Adams ring show that trends reported previously have continued: the two leading arcs are no longer visible, but the trailing two persist and have been relatively stable. Their mean motion is 820.1119 +/- 0.0003 degrees/day. This value has sufficient precision to rule out any of the previously proposed resonant confinement mechanisms.
Rosemary Cave, Queen Mary University of London
Uranus' Unstable Moons: Collision Outcomes and Implications
Orbital integrations of the Uranian satellite system demonstrate that the closest groups of satellites (Cressida-Desdemona and Cupid-Belinda-Perdita) will evolve to crossing orbits on timescales of 103 - 107 years (Duncan and Lissauer 1997, French and Showalter 2012). Thus, collisions between neighbouring Uranian satellites appear to be an inevitable aspect of the system's evolution. For low-velocity collisions in free space, simple mergers are a plausible outcome. However, when impacts occur near a primary's Roche zone, strong tidal forces complicate the outcomes. Previous analytic work, examining collisions of two solid spheres in a strong tidal field, demonstrates that accretion may be constrained by the mass ratio and bulk density of the impacting bodies (Ohtsuki 1993, Canup and Esposito 1995). Further, direct modelling of collisions between gravitational aggregates near Saturn's F-ring shows complex non-merging outcomes (Karjalainen 2007, Hyodo and Ohtsuki 2014). We are examining the outcomes of collisions between Uranus' unstable satellites. We are using the Rebound N-body code to conduct direct simulations of collisions in the tidal field of Uranus, treating satellites as gravitationally bound rubble piles. These models include a range of satellite densities, impact velocities and orientations appropriate to the most unstable satellites. At the meeting we shall present our model results, and discuss how collision outcomes constrain the bulk composition and interior structure of these satellites, and how these outcomes may inform the past and future evolution of the system.

Galaxies and Cosmology (Chair: Anna Lisa Varri)

Ann-Marie Madigan, CU Boulder

Tidal disruption events from eccentric nuclear stellar disks
Lopsided galactic nuclei, thought to form during gas-rich major mergers, are made up of stars on apsidally-aligned eccentric orbits. I will show how secular gravitational torques between the orbits not only maintains the stability of the nucleus but dramatically enhances the rates of tidal disruption events. This can explain their association with recent- and post-merger galaxies.
Heikki Salo, University of Oulu
N-body modeling of barlens galaxies: Boxy/Peanut/X observed at different viewing geometries
We use stellar dynamical N-body simulations to explore barlens galaxies, i.e. galaxies with lens-like central structures embedded in their bars, with a size about one-half of the narrow bar component. Because of their roundish isophotes, barlenses are often confused with classical bulges. However, growing evidence indicates that barlenses form a part of the bar, corresponding to the face-on projection of the vertically extended Boxy/Peanut/X central structures seen in edge-on barred galaxies (see Laurikainen et al. 2014, 2016, Athanassoula et al. 2015). B/P/X/barlens structures appear mostly in galaxies with stellar masses above 1010 solar masses. It has been suggested by Bland-Hawthorn & Gerhard (2016) that in face-on view also our Milky Way is likely to be a barlens galaxy. Here we review the morphological appearance of B/P/X/barlens galaxies (aspect ratio, size compared to the narrow bar) as a function of viewing inclination, by comparing synthetic images from simulations with the 3.6 micron data from S4G (Spitzer Survey of Stellar Structure in Galaxies). We demonstrate how the X/barlens morphology depends on the central mass concentration in galaxies; the pure barlens morphology requires steep inner rotation curves, while for shallower slopes the central structure still resembles a barlens, but shows boxy isophotes or X-signature even at low inclinations. This simulated behavior is confirmed with S4G data (Salo & Laurikainen 2017). We also use broadband SDSS colors and CALIFA DR3 data from literature, to analyze the ages and metallicities of the barlens components with respect to the narrow bar and the centralpeak of the galaxies. Finally, kinematic maps of the simulated galaxies are presented, illustrating the expected signatures of barlens component on the H3 and H4 Hermite-moments.
Juntai Shen, Shanghai Astronomical Obs.
A Potential Proxy of the Second Integral of Motion (I2) in a Rotating Barred Potential
The only analytically known integral of motion in a 2-D rotating barred potential is the Jacobi constant (EJ). In addition to EJ, regular orbits also obey a second integral of motion (I2) whose analytical form is unknown. We show that the time-averaged characteristics of angular momentum in a rotating bar potential resemble the behavior of the analytically-unknown I2. For a given EJ, regular orbits of various families follow a continuous sequence in the space of net angular momentum and its dispersion ("angular momentum space"). In the limiting case where regular orbits of the well-known x1/x4 orbital families dominate the phase space, the orbital sequence can be monotonically traced by a single parameter, namely the ratio of mean angular momentum to its dispersion. This ratio behaves well even in the 3-D case, and thus may be used as a proxy of I2. The potential proxy of I2 may be used as an efficient way to probe the phase space structure, and a convenient new scheme of orbit classification in addition to the frequency mapping technique.
Phil Breen, University of Edinburgh
Dynamical evolution of globular clusters in dark matter halos
The formation of globular clusters in a cosmological context is a topical open problem. One possible formation scenario is that globular clusters have formed in their own dark matter halos, and, as a result, some clusters may have retained it to the present day. In such a case, collisional processes taking place in the central regions of globulars may lead to the formation of a tenuous stellar envelope extending far beyond the tidal boundary of the parent cluster. The synergy between the astrometric mission Gaia and forthcoming multi-object spectrographs such as WEAVE will allow us to explore, with unprecedented accuracy, the outer regions of selected Galactic globular clusters, therefore it is particularly timely to consider to what extent the presence of dark matter is consistent with their dynamics and structure at large distances from the cluster centre. Driven by these motivations, we present the results of a series of direct N-body

simulations where globular clusters have been evolved self-consistently in a static dark matter potential. Special attention will be given to the exploration of the effects of the dark halo on the traditional phases of the long-term evolution of collisional systems and the dynamical interplay with other fundamental physical ingredients, such as stellar-mass black holes, will be discussed.

Raphaël Errani, University of Edinburgh

The effect of a disc on the population of cuspy and cored dark matter substructures in Milky Way-like galaxies

We use high-resolution N-body simulations to study the effect of a galactic disc on the dynamical evolution of dark matter substructures with orbits and structural parameters extracted from the Aquarius A-2 merger tree. Satellites are modelled as equilibrium N-body realizations of generalized Hernquist profiles with 2 × 106 particles and injected in the analytical evolving host potential at zinfall, defined by the peak of their mass evolution. We select all substructures with M200(zinfall) > 108 M⊙ and first pericentric distances rp < r200. Motivated by observations of Milky Way dwarf spheroidal galaxies, we also explore satellite models with cored dark matter profiles with a fixed core size rc = 0.8 as, where as is the Hernquist scale radius. We find that models with cuspy satellites have twice as many surviving substructures at z = 0 than their cored counterparts, and four times as many if we only consider those on orbits with rp < 0.1 r200. For a given profile, adding an evolving disc potential reduces the number of surviving substructures further by a factor of <2 for satellites on orbits which penetrate the disc (rp < 20 kpc). For large rp, where tidal forces and the effect of the disc become negligible, the number of satellites per pericentre bin converges to similar values for all four models.

Toshio Fukushima, National Astronomical Observatory of Japan

Numerical computation of gravitational field of general extended body and its application to rotation curve study of galaxies

Reviewed are recently developed methods of the numerical integration of the gravitational field of general two- or three-dimensional bodies with arbitrary shape and mass density distribution: (i) an axisymmetric infinitely-thin disc (Fukushima 2016a, MNRAS, 456, 3702), (ii) a general infinitely-thin plate (Fukushima 2016b, MNRAS, 459, 3825), (iii) a plane-symmetric and axisymmetric ring-like object (Fukushima 2016c, AJ, 152, 35), (iv) an axisymmetric thick disc (Fukushima 2016d, MNRAS, 462, 2138), and (v) a general three-dimensional body (Fukushima 2016e, MNRAS, 463, 1500). The key techniques employed are (a) the split quadrature method using the double exponential rule (Takahashi and Mori, 1973, Numer. Math., 21, 206), (b) the precise and fast computation of complete elliptic integrals (Fukushima 2015, J. Comp. Appl. Math., 282, 71), (c) Ridder's algorithm of numerical differentiaion (Ridder 1982, Adv. Eng. Softw., 4, 75), (d) the recursive computation of the zonal toroidal harmonics, and (e) the integration variable transformation to the local spherical polar coordinates. These devices succesfully regularize the Newton kernel in the integrands so as to provide accurate integral values. For example, the general 3D potential is regularly integrated as \Phi (\vec{x}) = - G \int_0^\infty (\int_{-1}^1 (\int_0^{2\pi} \rho (\vec{x}+\vec{q}) d\psi) d\gamma) q dq, where \vec{q} = q (\sqrt{1-\gamma^2} \cos \psi, \sqrt{1-\gamma^2} \sin \psi, \gamma), is the relative position vector referred to \vec{x}, the position vector at which the potential is evaluated. As a result, the new methods can compute the potential and acceleration vector very accurately. In fact, the axisymmetric integration reproduces the Miyamoto-Nagai potential with 14 correct digits. The developed methods are applied to the gravitational field study of galaxies and protoplanetary discs. Among them, the investigation on the rotation curve of M33 supports a disc-like structure of the dark matter with a double-power-law surface mass density distribution. Fortran 90 subroutines to execute these methods and their test programs and sample outputs are available from the author's website: https://www.researchgate.net/profile/Toshio_Fukushima/ [3]

Indranil Banik, University of Saint Andrews

The High Velocity Galaxy Challenge to ΛCDM in the Local Group

In the Local Group (LG), Andromeda (M31) is approaching the Milky Way (MW) at ~110 km/s despite the large scale cosmic expansion. To turn it around locally to this extent, their combined mass must lie in a narrow range of values. This constrains the

gravitational field in the LG as there are no other objects of similar masses. We have conducted calculations solving test particle trajectories in this gravitational field using a 2D dynamical model including Cen A and the LMC (MNRAS, 459, 2237). Although few objects have radial velocities (RVs) much below the predictions of the best-fitting model, some have RVs much above them, sometimes by as much as 100 km/s. This situation persists even when we used a 3D model including perturbers and satellites (MNRAS, 467, 2180). The observations may be explained by a past close flyby of the MW and M31, which arises in Modified Newtonian Dynamics (MOND) but not ΛCDM. In this context, a simplified calculation suggests that the recently discovered plane of satellites around the MW and a similar plane around M31 could be explained by a past MW-M31 flyby, but only if they orbit within a particular plane. We used this information in a more detailed MOND simulation of the flyby and its effect on the rest of the LG, treating it as a cloud of ~3×105 test particles. The high speeds of the MW and M31 at pericentre allow for efficient gravitational slingshots of these particles. Those flung out to the greatest distance tend to lie very close to the MW-M31 orbital plane, probably because the greatest impulses occur for objects flung out almost parallel to the motion of the perturber. I will describe this simulation and recent work (Arxiv: 1701.06559) showing that LG dwarfs with the most anomalously high RVs (relative to our 3D model) indeed lie close to a plane oriented similarly to our expected MW-M31 orbital plane based on considering their satellite systems. This plane of distant LG dwarfs passes within 140 kpc of the MW and M31 and just 6 kpc from their mid-point despite being 1 Mpc across. Treating the 6 high-velocity galaxies as isotropically distributed yields only a 0.16% chance of having these observed characteristics, which we focus on because they should arise naturally in MOND.

Saturn's Rings and Ring-Satellite Dynamics (Chair: Matt Tiscareno))

Maryame El Moutamid, Cornell University
On what we have learned about the system of Saturn thanks to Cassini
This is the end; Cassini will crash into Saturn’s atmosphere within few months, providing unique data and results thanks to the last orbits. After losing contact with us, it will become part of the planet itself. By September 2017, Cassini will have spent 13 years in orbit around Saturn, during this period, scientists from the world have collected data from many instruments and have learned a great deal about the planet itself, its rings and satellites, and the connection between them. I will present some of the results on what we have learned about the evolution of the moons, on the main rings of Saturn and their dynamical connection with the interior of the planet.
Silvia Giuliatti-Winter, Campus De Guaratingueta UNESP
The Long Term Evolution of the Satellites Aegaeon, Methone, Anthe, and Pallene, and the Nearby Region
Although the orbital characterization of the satellites, Aegaeon, Methone, Anthe, and Pallene, has been carried on by several authors, their long term evolutions have not been studied in details so far. In this work we present the numerical exploration of the long term evolution, up to 105 yrs, for the small moons in a system formed by Saturn, considering up to J6 in its zonal harmonics, and the five largest moons located close to them. Through frequency analysis we determined the stability of the moons and characterize the dynamical behavior of a wide region of the geometric phase space, semimajor axis (a) versus eccentricity (e). Our results showed that: i) if the migration of the largest moons, mainly Mimas, is slow enough, the stability time for the small moons would be at least ~ 0.4 Myr for Aegaeon, Methone, and Anthe, and up to 64 Myrs for Pallene; ii) Aegaeon remains trapped in the 7:6 Corotation Eccentric Resonance with Mimas, with maximum variations of only ~6.4 km in a. Its e remains small, and variations in i imply maximum excursions above Saturn’s equatorial plane of 4.7 km, iii) regarding the G ring, 30% of the ring particles collide with Aegaeon, while the remaining are stirred in their i (inclination) up to 0.0056deg in average. This implies a vertical widening of 17 km in just ~18 yrs of an initially flat distribution of particles, iv) despite the larger size of Pallene, compared to Aegaeon, Methone or Anthe, this small moon is unable to efficiently clean up its orbit, due to its values of e and i. The average final inclination of the ring

particles is 0.001173deg, which leads to a vertical width of ~4.5 km. We also analyzed the orbital evolution of a sample of dust particles ejected from the surface of Pallene when interplanetary dust particles collide onto its surface. From the numerical simulation results, also under the effects of the solar radiation forces, we found that above 90% of the initial set of 1μm sized particles are removed by collisions before 40 yrs, regardless its initial velocity (1, 5 or 10 times the escape velocity), while about 60% of 5μm sized particles are lost after 100 yrs and less than 35% of the initial set of 10μm sized particles are lost in the same time interval .

Aurélien Crida, Observatoire de la Côte d'Azur

Formation of Janus and Epimetheus from Saturn's rings as coorbitals, thanks to Mimas' 2:3 inner Mean Motion Resonances

Janus and Epimetheus orbit Saturn at 151461 km on average, on mutual horseshoe orbits with orbital separation 50 km, exchanging position every 4 years. This configuration is unique and intriguing : Lissauer et al. (1985) have shown that their orbital separation should converge to zero in about 20 Myrs only, and no satisfactory model for the origin of this co-orbital resonance exists yet. Charnoz et al. (2010) have shown that Janus and Epimetheus probably formed from the spreading of the rings beyond the Roche radius. Here, we study this phenomenon in the frame of the elliptical restricted 3-body problem, where ring particles are perturbed by mean motion resonances with the outer satellite Mimas. Two types of resonances play different roles. The Lindblad resonance (LR) confines the rings radially, and prevents their spreading (like the B-ring into the Cassini division). The Corotation resonance (CR) confines the rings azimuthally in two capture sites (akin Neptune's arcs). Because of Saturn's J_2, the CR is 130 km closer to Saturn than the LR. A few hundred million years ago, the 2:3 mean motion resonances with Mimas were just inside the Roche radius ; hence the rings could not spread and the two capture sites were full of ring material. When Mimas migrated outwards so that its 2:3 mean motion resonances receded past the Roche radius, the captured material agglomerated into two bodies of ~10^{15} kg on the exact same orbit. These bodies then migrated outwardstogether due to their interaction with the rings, in mutual horseshoe orbits. The rings then spawn new small satellites, eventually accreted by the proto-Janus and the proto-Epimetheus following the pyramidal regime of the ring spreading model (Crida & Charnoz 2012). The two bodies then grow in mass following a Fibonacci sequence, and this excites their orbital separation, leading to a configuration close to the present one.

Jing Luan, University of California at Berkeley

How tides get dissipated in Saturn? A question probably answerable by Cassini

Tidal dissipation inside a giant planet is important in understanding the orbital evolutions of its natural satellites and perhaps some of the extrasolar giant planets. The tidal dissipation is conventionally parameterized by the tidal quality factor, Q. The corresponding tidal torque declines rapidly with distance adopting constant Q. However, the current fast migration rates of some Saturnian satellites reported by Lainey et al. (2015) conflict this conventional conceptual belief. Alternatively, resonance lock between a satellite and an internal oscillation mode or wave of Saturn, proposed by Fuller et al. (2016), could naturally match the observational migration rates. However, the question still remains to be answered what type of mode or wave is locked with each satellite. There are two candidates for resonance lock, one is gravity mode, and the other is inertial wave attractor. They generate very different gravity acceleration anomaly near the surface of Saturn, which may be distinguishable by the data to be collected by Cassini during its proximal orbits between April and September, 2017. Indicative information about the interior of Saturn may be extracted since the existence of both gravity mode and inertial wave attractor depends on the internal structure of Saturn.

Benoit Noyelles, University of Namur

The relation between the geophysical activity of the Saturnian satellites and the Cassini Division

The Cassini Division is a 4,500 km wide gap in the rings of Saturn, which inner edge is at the exact 2:1 Inner Lindblad Resonance with Mimas. We here present our latest results regarding the formation and the stability of the Division, in combining N-body simulations of the main satellites of Saturn with hydrodynamical simulations of the rings, with the 1-D code Hydrorings (Charnoz et al. 2011). We show that an inward migration of

Mimas over 8,000 to 9,000 km would create the Division in less than 10 Myr, and we get a final mass distribution in the rings that would look like the density distribution derived from optical depth observations assuming a uniform mass extinction coefficient for the ring particles. We also investigated two sources of inward migration of Mimas, i.e. an intense dissipation of Mimas, and an intense dissipation in Enceladus which would have been locked in a mean-motion resonance with Mimas, provoking the inward migration of the two satellites. The scenario involving a past intense dissipation in Mimas keeps the system of Saturn stable, but is inconsistent with the observed age of the surface of Mimas. However, a past intense dissipation in Enceladus is acceptable from a geophysical point of view owing to its present activity, but would have required an eccentricity so high that the system of Saturn would have been destabilized.

Thursday, June 15

Cassini Ring-Grazing Orbits and Grand Finale, Part 1 (Chair: Marina Brozovic)

Pierre-Yves Longaretti, IPAG
Global modes in Saturn's main rings. Theoretical background and current issues
The dynamics of dense ring systems may conveniently be divided into two main topics: local structures, mostly driven be local, incoherent instabilities (most prominently, self-gravitational wakes and local viscous overstabilities) and global structures, involving in particular non-axisymmetric features over the whole extent in azimuth. The latter include density and bending waves, global narrow ring modes and edge modes; these structures can be globally viscously overstable. All global modes have a common dynamical origin and can be described in a unified dynamical framework, which will be reviewed in the first part of the talk. In particular, all planar narrow ring modes and edge modes can be described as trapped density waves and theoretically investigated as a nonlinear eigenvalue problem. The second part of the talk will focus on salient problems, some of which were discovered and characterized during the Cassini mission. These include, e.g., the numerous edge modes observed at gap edges and narrow ring edges, the peculiar structure of the B ring edge and the alternating series of gaps and rings populating the Cassini division. The possible dynamical origin of these structures will be reviewed; if available at the time of the conference, new numerical simulations investigating the dynamics of the B ring edge will be presented.
Glen Stewart, Univ. of Colorado
Straw Formation and Enhanced Damping of Strong Density Waves in Saturn's Rings
High resolution Cassini images of strong density waves in Saturn's rings often show kilometer-scale structures in the wave troughs that are sometimes described as straw-like structures. These structures are likely formed by transient gravitational instabilities within the density wave and have the potential to greatly enhance the local viscous angular momentum transport and thereby limit the maximum amplitude of the density wave. A Hamiltonian theory for density waves has been developed that can describe the rate of local gravitational instabilities in the wave train. The Hamiltonian for single particle motion in the vicinity of an inner Lindblad resonance with a Saturnian satellite can be formulated such that the angle variable conjugate to the radial action is the resonant argument for the resonance. The density wave can then be derived using Hamiltonian perturbation methods to remove the satellite perturbation such that the transformed radial action and conjugate angles include the usual solution for self-gravitating density waves. Local gravitational instabilities in the density wave can now be formulated using a linearized collisionless Boltzmann equation that is expressed in terms of the transformed action-angle variables that contain the density wave solution. The gravitational potential of the linearized perturbation is found to be enhanced by a factor of ten or more in strong density waves, which likely explains the

observation of kilometer-scale structures in these waves. The Hamiltonian formalism can also be used to derive an enhanced effective viscosity that results from these straw-like structures.

Marius Lehmann, University of Oulu

The role of collective self-gravity in the nonlinear evolution of viscous overstability in Saturn's rings

We investigate the influence of collective self-gravity forces on the nonlinear evolution of the viscous overstability in Saturn's dense rings. Local N-body simulations, incorporating vertical and radial collective self-gravity are performed. Vertical self-gravity is mimicked through an increased frequency of vertical oscillations, while radial self-gravity is approximated by solving the Poisson equation for a thin disk in Fourier space. Direct particle-particle forces are omitted, while the magnitude of radial self gravity is controlled by assigning a variable surface mass density to the system's homogeneous ground state. We compare our simulations with large-scale isothermal and non-isothermal hydrodynamic model calculations, including radial self-gravity and employing transport coefficients derived in Salo et al. (2001). We concentrate on optical depths τ=1.5-2, appropriate to model Saturn's dense rings. Our isothermal and non isothermal hydrodynamic results in the limit of vanishing self-gravity compare very well with the studies of Latter & Ogilvie (2010) and Rein&latter (2013), respectively. With non-vanishing radial self-gravity we find that the wavelengths of saturated overstable wave trains are located in close vicinity of the local minimum of the nonlinear dispersion relation for a particular surface density. Good agreement is found between non-isothermal hydrodynamics and N-body simulations for disks with strong radial self-gravity, while the largest deviations occur for a weak but non-vanishing self-gravity. The resulting saturation wavelengths of the viscous overstability for moderate and strong radial self-gravity (λ~ 200-300m) agree reasonably well with the length scale of periodic micro structure in Saturn's inner A and B ring, as found by Cassini.

Joseph Spitale, Planetary Science Institute

Saturn's Misbegotten Moonlets

Saturn's rings are interspersed with numerous narrow (tens of km wide) gaps. Two of the largest of these gaps — Encke and Keeler — contain satellites — Pan and Daphnis — that maintain their respective gaps via the classical Goldreich/Tremaine-style shepherding mechanism wherein angular momentum is transferred across the essentially empty gap via torques acting between the satellites and the ring. Other prominent gaps are shepherded by resonances with external satellites or planetary modes: Mimas shepherds the outer edge of the B ring, clearing the inner part of the Cassini Division, Titan shepherds the Columbo ringlet / gap, and the Maxwell ringlet / gap is likely maintained by a resonance with a planetary mode. Prior to Cassini, it was expected that all of the gaps would be shepherded in a similar manner. However, many small gaps do not correspond with known resonances, and no satellites were spotted within those gaps during Cassini's prime and extended mission. To address this issue, a series of Cassini imaging observations were planned to examine 11 gaps in the C ring and Cassini division at a resolution and longitudinal coverage sufficient to either discover the shepherds or rule out their presence. The survey discovered no embedded satellites. Longitudinal coverage was incomplete, but within longitudes covered by the survey, satellites are ruled out to sizes in the 100-m range, far too small keep the observed gaps open. It is possible (about even odds) that there could be a larger satellite residing at a longitude not covered in the survey, but the probability that the survey was unfortunate enough to miss significant satellites in all 11 gaps is exceedingly small (~0.002%). Moreover, these gaps appear in earlier imaging sequences, with some high-resolution coverage, so the true probability is smaller yet. Therefore, a new theory is likely needed to explain the presence of the gaps.

Cassini Ring-Grazing Orbits and Grand Finale, Part 2 (Chair: Glen Stewart)

Linda Spilker, JPL

Cassini's Grand Finale and Recent Science Highlights

After almost 13 years in Saturn orbit, the Cassini-Huygens mission has entered its final

year of data collection. Cassini will return its final bits of unique data on 15 September 2017 as it plunges into Saturn's atmosphere, vaporizing and satisfying planetary protection requirements. Since early 2016 Cassini's orbital inclination was slowly increased towards its final inclination. In November Cassini transitioned to a series of 20 orbits with periapses just outside Saturn's F ring that included some of the closest flybys of the tiny ring moons and excellent views of the F ring and outer A ring. Cassini's final close flyby of Titan in April 2017 propelled it across Saturn's main rings and into its final orbits. Cassini's Grand Finale began in April 2017 and is comprised of 22 orbits at an inclination of 63 degrees. Cassini is repeatedly diving between the innermost ring and Saturn's upper atmosphere providing insights into fundamental questions unattainable during the rest of the mission. It is the first spacecraft to explore this region. These close orbits provide the highest resolution observations of both the rings and Saturn, and direct in situ sampling of the ring particles' composition, plasma, Saturn's exosphere and the innermost radiation belts. Saturn's gravitational field will be measured to unprecedented accuracy, providing information on Saturn's interior structure and mass distribution in the rings. Probing the magnetic field will give insight into the nature of the magnetic dynamo and the true rotation rate of Saturn's interior. The ion and neutral mass spectrometer will sniff the exosphere and upper atmosphere and examine water-based molecules originating from the rings. The cosmic dust analyzer will sample particle composition from different parts of the main rings. Recent science highlights and science objectives from Cassini's final orbits will be discussed. This work was carried out in part at the Jet Propulsion Laboratory, California Institute of Technology, under contract with NASA. Copyright 2017 California Institute of Technology. Government sponsorship is acknowledged.

Matthew Tiscareno, SETI Institute

Targeted flyby images of propellers in Saturn's A ring

As part of its two-part end-of-mission maneuvers, the Cassini has targeted three "propeller moons" for close-range flybys, obtaining images that greatly improve on all previous images in terms of resolution and detailed structure. Propeller moons are ~1 km in size and are embedded in the disk of Saturn's A ring (Tiscareno et al. 2010, ApJL). Unlike the moons Pan and Daphnis, propeller moons have insufficient mass to carve out a fully circumferential gap; instead, we see a propeller-shaped disturbance around the moon (which itself is unseen) as the moon's attempted gap is filled back in, due to the dynamical viscosity of the ring particles. The Cassini Imaging Science Subsystem (ISS) has obtained images of the propeller moon "Santos-Dumont" on both the lit and unlit sides of the rings, and of "Earhart" on the lit side. As of this writing, a final targeted flyby of "Bleriot" on the unlit side of the rings has yet to take place. The resolution of these images is at least 3x to 4x better than those of nearly all previous propeller images, and at least 2x better than those of a small handful of the best previous propeller images. We will present maps of of the propeller structures, with enhanced ability to convert brightness to optical depth and surface density due to information from both the lit and unlit sides of the rings. The images contain more complex structure than is predicted by simple models, which we will describe, and for which we will comment on likely explanations. The central moonlet of each propeller (which has never been seen) should be a couple of pixels across, but we cannot confirm whether they are seen in these images or whether they are obscured by stirred-up ring material.

Matthew Hedman, University of Idaho

Drifting waves in Saturn's C ring, evidence for changes in Saturn's interior

Recent analyses of spiral density waves in Saturn's C ring have revealed that many of these waves are generated by either normal-mode oscillations or asymmetries in Saturn's interior. The waves generated by normal-mode oscillations exhibit remarkably stable pattern speeds, indicating that the oscillations inside the planet that generate these waves have frequencies that remain constant for years to decades. However, close inspection of the waves with pattern speeds close to Saturn's rotation rate reveals that several of these waves have been moving inwards over the course of the Cassini mission at rates of around 1 kilometer per year. These "drifting waves" suggest that the frequencies of the relevant driving forces are increasing over time. Hence some aspect of Saturn's internal structure must be slowly changing on decadal timescales. Furthermore, since these waves are generated by forces that are not strictly periodic, they provide

new opportunities to examine how disturbances propagate within dense rings.
Philip Nicholson, Cornell Univ.
The puzzling structure in Saturn's outer B ring
As first noted in Voyager images, the outer edge of Saturn's B ring is strongly perturbed by the 2:1 inner Lindblad resonance with Mimas (Porco \etal\ 1984). Cassini imaging and occultation data have revealed a more complex situation, where the expected resonantly-forced m=2 perturbation with an amplitude of 33~km is accompanied by free modes with m=1, 2, 3, 4 and 5 (Spitale & Porco 2010, Nicholson \etal\ 2014a). To date, however, the structure immediately interior to the ring edge has not been examined carefully. We have compared optical depth profiles of the outer 1000~km of the B ring, using a large set of stellar occultations carried out since 2005 by the Cassini VIMS instrument. A search for wavelike structure, using a code written to search for hidden density waves (Hedman \& Nicholson 2016), reveals a significant signature at a radius of ~117,150 km with a radial wavelength of ~110 km. This appears to be a trailing spiral with m=1 and a pattern speed equal to the local apsidal precession rate, $\dpi\simeq5.12\dd$. Further searches for organized large-scale structure have revealed none with m=2 (as might have been expected), but several additional regions with significant m=1 variations and pattern speeds close to the local value of $\dpi$. At present, it is unclear if these represent propagating spirals, standing waves, or perhaps features more akin to the eccentric ringlets often seen within gaps in the C ring and Cassini Division (Nicholson \etal\ 2014b, French \etal\ 2016). Comparisons of sets of profiles from 2008/9, 2012-14 and 2016 seem to show that these structures are changing over time.
Carl Murray, Queen Mary University of Londonbr>High resolution Cassini observations of Saturn’s A ring in the vicinity of object "Peggy"
Cassini images of the edge of Saturn’s A ring strongly suggest the presence of an embedded object (nicknamed “Peggy”) producing localised, time-varying structure due to its gravitational perturbation of nearby ring material. "Peggy"’s gravitational signature has been tracked since its discovery in 2013 and, although the deduced semi-major axis has varied between 136766 km and 136775 km, the value has always been within 10 km of the edge location as determined by El Moutamid et al. (2016). In early 2016 a second object was detected, trailing “Peggy” at a larger semi-major axis, with both objects having been tracked since then. Here we discuss the current state of our understanding of this unusual object and its orbital evolution, making use of the most recent, high resolution observations obtained both before and during the ring-grazing and grand finale orbits of the Cassini spacecraft. These images will then be compared with numerical simulations of the effect of an embedded satellite on adjacent, orbiting particles with the goal of obtaining the mass and dimensions of the object.

Small Bodies, Stability, and Instability (Chair: Aswin Sekhar)

Michael Cahill, Univ. of Wisconsin, Washington County
Use of the Digamma Function in Statistical Astrophysics Distributions
Relaxed astrophysical statistical distributions may be constructed by using the inverse of a most probable energy distribution equation giving the energy ei of each particle in cell i in terms of the cell’s particle population Ni. The digamma mediated equation is A + Bei = Ψ(1+ Ni), where the constants A & B are Lagrange multipliers and Ψ is the digamma function given by Ψ(x) = dln(x!)/dx. Results are discussed for a Monatomic Ideal Gas, Atmospheres of Spherical Planets or Satellites and for Spherical Globular Clusters. These distributions are self-terminating even if other factors do not cause a cutoff. The examples are discussed classically but relativistic extensions are possible.
Apostolos Christou, Armagh Observatory and Planetarium
Orbital evolution and escape of Martian Trojans due to the Yarkovsky effect
Recently it was shown that the Yarkovsky effect can lead to significant orbit change for Trojans of Mars [1,2] and that the orbital distribution of observed Trojans is consistent with a negative along-track acceleration of the same functional form as seasonal yarkovsky; this feature was used to constrain the age of the Eureka family of Mars Trojan asteroids [2]. In contrast, the Yarkovsky effect appears to have a negligible role in

shaping observed families of Jupiter Trojans [3]. To explore the evolution and end states of Trojans evolved by the Yarkosky effect, I have numerically integrated test particles under a model of the diurnal variant and for different values of the acceleration strength up to 10-2 AU/Myr for da/dt outside the resonance. I use as a starting point the orbits of the three largest Martian Trojans: 5261 Eureka, (101429) 1998 VF31 and (121514) 1999 UJ7. I find, as in [2], that the evolution of the inclination I and the libration amplitude L depends on the sign of the acceleration and is essentially deterministic. Considering the rate of change of the Tisserand constant [5,6] leads to a simple analytical expression that reproduces well the inclination evolution of the Trojans. The evolution of e is somewhat more stochastic, probably due to chaotic diffusion [4] and/or the influence of Mars' eccentricity [2]. Trojans escape upon reaching the boundaries of stability domains mapped out in [4], demarcated by resonances with principal secular modes and the Kozai resonance. The mechanism of escape is by increasing e and/or the libration amplitude to the point of allowing close encounters with Mars. During the presentation I will describe the ensemble evolution of Trojans under Yarkovsky, how it is related to the lifetime in the 1:1 resonance and discuss the implications for Trojan stability at Earth and Jupiter.
[1] Christou, A.A., 2013, Icarus, 224, 144. [2] Ćuk, M., Christou, A.A., Hamilton, D.P., 2015, Icarus, 252, 339. [3] Milani, A., Knezević, Z., Spoto, F., Cellino, A., Novaković, B., Tsirvoulis, G., 2017, Icarus, 288, 240. [4] Scholl, H., Marzari, F., Tricarico, P., 2005, Icarus, 175, 397. [5] Hamilton, D.P., 1994, Icarus, 109, 221 [6] Liou, J. C., Zook, H. A., 1997, Icarus, 128, 354.
Seth Jacobson, University of Bayreuth
Origin of the Mars Trojans
The Mars Trojan Eureka and associated fragments possess a rare olivine-rich minerology spectrally identified as A-type. High olivine content rocks are typically associated with the interiors of differentiated bodies like Mars. Here, we show that impact ejecta from Mars is likely to have been captured as Mars Trojans in the final stages of terrestrial planet formation. We simulated the ejection of thousands of asteroids from Mars and modeled with the Symba N-body code how their orbits evolved with time due to perturbations from Mars and the other 7 planets. Scholl et al. identified a stable region in eccentricity (e < 0.2) and inclination (10° + 20° (e / 0.25) < i < 30) for Mars Trojans, so we measured what fraction of ejecta obtained these eccentricities and inclinations as a function of semi-major axis away from Mars. During the end stages of planet formation, the semi-major axis of Mars changed significantly for the final time. This last jump is responsible for capturing the Mars Trojans. Using simulations of terrestrial planet formation, we assessed the size and timing of this last jump relative to planetesimals accretion on Mars. By combining this analsysis with the orbital evolution of impact ejecta, we obtained Mars Trojan production rates of order 1 per 105. The production rate of Mars Trojans as a function of time between the impact which created the impact debris on Mars and the final semi-major axis jumpt of Mars. The production rate is per 105 ejecta, since it is expected that a Borealis Basin sized impact on Mars would create approximately that much debris with a diameter of 2 km or greater. Clearly, obtaining the Eureka progenitor from Mars ejecta is likely.
Daohai Li, Armagh Observatory
Dispersion of the Himalia family of jovian irregular satellites by planetesimal encounters
Giant planets are believed to have migrated significant radial distances due to interaction with a primordial planetesimal disk (Tsiganis et al. 2005). This process profoundly sculpted the solar system, shaping the distribution of the different types of heliocentric objects: the giant planets, the Trojans, the Main Asteroid Belt and the KBOs. Meanwhile, the same migration may have influenced the distribution of objects in the local planetocentric system as well. Since migration is achieved mainly by planet-planetesimal encounters, we focus on irregular satellites far from the host, thus susceptible to planetesimal perturbations. Specifically, we aim to reproduce a puzzling feature of the jovian Himalia group of prograde satellites: a wide spread in a and e, with all group members being >200 m/s from Himalia and apparently too high to be consistent with a purely collisional origin. Here we investigate the evolution of a pre-existing Himalia group during planetary migration. We do this in a two-step procedure. Firstly, we perform migration simulations and record the states of planetesimals approaching Jupiter. Secondly, a nascent, closely-packed Himalia group

with velocity dispersion of a few 10 m/s is integrated under the gravitational disturbance of the planetesimal fly-bys. We find that these planetesimal encounters disperse the group dramatically, bumping $\sim 60\%$ of the members to >200 m/s with respect to Himalia. Particularly, a and e suffer the most variation while the change in i is often limited, matching the actual values for the observed group fairly well. Current models posit extensive collisional processing of the irregular satellite population following the planet migration phase (Bottke et al. 2010). In evaluating the collisional probability between a group member and Himalia, we find that the closer they are, the more likely that collisions occur. This suggests that members adjacent to Himalia are more likely to be collisionally removed, further modifying the group. We propose that, if the formation of the Himalia group occurred before the end of the migration phase, planetesimal-induced dispersion must have contributed significantly to the orbital distribution of the observed group.

Othon Winter, UNESP

Dynamical Evolution of NEAs: A New Classification

The near Earth asteroids (NEAs) are usually classified according to their orbital characteristics into four groups: Atens, Apollo, Amor and Atira. An Atens has a semi-major axis of less than 1 au and aphelion distance greater than the Earth's perihelion distance. An Amor has perihelion distance greater than the Earth's aphelion distance and aphelion smaller than 1.3 au. An Apollo has semi-major axis of more than 1 au and perihelion distance smaller than the Earth's aphelion distance. An Atira has aphelion distance smaller than Earth's perihelion distance. However, this is a static classification, based on their current osculating orbital elements. The NEAs live in a region highly perturbed by the terrestrial planets. In general, their lifetime is of the order of 10 Myrs. Most of them cross the border from one group to another during their lifetime, that means they temporarily belong to a given group. So, the question is how would they be classified according to their dynamical orbital evolution? In the present work is studied the temporal orbital evolution of the NEAs. There were performed numerical simulations of a representative sample of NEAs under the gravitational influence of all planets and the Sun. Their dynamics is dominated by the gravitational interactions with the terrestrial planets. A single close encounter with one of this planets can move an asteroid from one group to another. We pay special attention to their mobility as a function of their initial location in the semi-major axis versus eccentricity plane (a x e), and consequently in their transition between the groups. The results reveal some sort of patterns to be used in a new classification of the NEAs in terms of dynamical orbital evolution.

Brian Anderson, University of Southern California

Invariant Manifolds and The Transport of Asteroid 2006 RH120

Poincaré stated that “periodic orbits” are the only means by which we can understand the dynamics of differential equations. The objects he really meant are the “invariant manifolds of periodic orbits” which he discovered. It was the intersection of invariant manifolds that led to his discovery of homoclinic orbits and deterministic chaos in his celebrated work on the 3 body problem. Koon, Lo, Marsden, Ross 2000 explained the theory for how invariant manifolds of periodic orbits around the L1 and L2 Lagrange points control the transport of small bodies between the 2:3 resonance outside of Jupiter’s orbit to the 3:2 resonance inside of Jupiter’s orbit. This resonance transition is exhibited by many members of the Jupiter Family of comets as shown by Howell, Marchand, and Lo 2001 computed in JPL ephemeris model. These comets include Gehrels 3, Helin-Roman-Crockett, Oterma, and others. We present some recent work on the role of invariant manifolds for the capture of Earth’s first minimoon, asteroid 2006 RH120. It was captured around the Earth-Moon system for approximately 1 year. We show how the manifolds of halo orbits at Earth’s L1 and L2 provide the dynamical channels for the temporary capture by the Earth and its eventual escape from the Earth. The Moon further complicates the dynamics during the capture phase. The history of the asteroid orbit before and after the temporary capture phase is dominated by a series of complex resonance transitions via the invariant manifolds of unstable resonant orbits. This same dynamics is used to design satellite tours to the moons of Jupiter and Saturn such as Europa and Titan.

Posters

Dimitri Veras, University of Warwick
Total, partial and annular eclipse geometry of exoplanetary systems at exo-syzygy
The total eclipse which will occur in just two months on August 21st, 2017 over the United States reminds us that conjunctions and oppositions frequently occur in planetary systems. However, eclipse-related phenomena are usually described from an Earth-centric perspective. Space missions to different parts of the Solar system, as well as the mounting number of known exo-planets in habitable zones and the possibility of sending featherweight robot spacecraft to them, prompt broader considerations. Here, we derive the geometry of eclipses, transits and occultations from a primarily exo-Earth viewpoint, and apply the formulation to the Solar system and three types of three-body extrasolar planetary systems: with 1 star and 2 planets (Case I), with 2 stars and 1 planet (Case II), and with 1 planet, 1 star and 1 moon (Case III). We derive the general conditions for total, partial and annular eclipses to occur at exo-syzygy, and implement them in each case in concert with stability criteria. We then apply the formalism to the TRAPPIST-1, Kepler-444 and Kepler-77 systems -- the first of which contains multiple potentially habitable planets — and provide reference tables of both Solar system and TRAPPIST-1 syzygy properties. We finally detail a basic algebraic algorithm which can be used to quickly characterize eclipse properties in any three-body system.
Aswin Sekhar, Centre for Earth Evolution and Dynamics
Change in Minimum Orbit Intersection Distance due to General Relativistic Precession in Small Solar System Bodies
One of the greatest successes of Einstein's General Theory of Relativity (GR) was the correct prediction of the perihelion precession of Mercury. The closed form expression to compute this precession tells us that substantial GR precession would occur only if the bodies have a combination of both moderately small perihelion distance and semi-major axis. Minimum Orbit Intersection Distance (MOID) is a quantity which helps us to understand the closest proximity of two orbits in space. Hence evaluating MOID is crucial to understand close encounters and collision scenarios better. In this work, we look at the possible scenarios where a small GR precession in argument of pericentre can create substantial changes in MOID for small bodies ranging from meteoroids to comets and asteroids. Previous works have looked into neat analytical techniques to understand different collision scenarios and we use those standard expressions to compute MOID analytically. We find the nature of this mathematical function is such that a relatively small GR precession can lead to drastic changes in MOID values depending on the initial value of argument of pericentre. Numerical integrations were done with the MERCURY package incorporating GR code to test the same effects. A numerical approach showed the same interesting relationship (as shown by analytical theory) between values of argument of pericentre and the peaks or dips in MOID values. There is an overall agreement between both analytical and numerical methods. We find that GR precession could play an important role in the calculations pertaining to MOID and close encounter scenarios in the case of certain small solar system bodies (depending on their initial orbital elements) when long term impact risk possibilities are considered. Previous works have looked into impact probabilities and collision scenarios on planets from different small body populations. This work aims to find certain sub-sets of small bodies where GR could play an interesting role. Certain parallels are drawn between the cases of asteroids, comets and small perihelion distance meteoroid streams.
Robert Jedicke, University of Hawaii
Broken Plane Delta-v Calculation For Rapid Assessment of Synthetic Asteroid Targets for In-situ Resource Utilization
We have developed a simplified mission model to estimate the quantity of deliverable water from small NEOs to distant retrograde lunar orbit (DRLO) as a function of Earth-return trip time and Δv. Our model is designed to be analytically simple, computationally efficient, and close enough to optimal to provide a realistic but

conservative assessment of the relevant parameters. The challenge stems from the fact that we are not considering a mission to a specific, known target, but rather missions to the ensemble of NEOs in a synthetic population. To further simplify the analysis we treat Earth's heliocentric orbit as circular with a semi-major axis of 1 au and zero inclination.

Marina Brozovic, Jet Propulsion Laboratory/Caltech

Lost and found: orbital uncertainties of the irregular satellites of the outer planets

The irregular satellites of the outer planets are a diverse population of relatively small objects that reside in orbits with high inclinations and eccentricities. More than 100 irregular satellites have been discovered to date, but many of these objects have poorly determined orbits due to lack of long observing arcs. We report on an orbital update of the JPL ephemerides. We used a linear covariance mapping to propagate orbital uncertainties over time. The projections of these uncertainties on the plane-of-sky (R.A. and decl.) predict which satellites are in need of the follow-up astrometry. This linear covariance mapping also identifies satellites that have the plane-of-sky uncertainties larger than 1000 arcseconds and that are effectively lost. Both Jupiter and Saturn have >15% of their irregular populations lost. Uranus and Neptune have very few known irregulars to begin with, 9 and 6 respectively, and for all but one (Neso, a satellite of Neptune), the orbits are well determined. We show that the uncertainties vary in time due to orbital geometry projection on the plane-of-sky and that it is possible to identify the times when recovery observations are more likely to succeed. However, many of these objects are faint, H>23 mag, which puts a requirement on large telescopes as the observing instruments.

Thomas Rimlinger, University of Maryland, College Park

Ringing in an HNBody Upgrade

We are in the process of developing a useful extension to the N-body integrator HNBody (Rauch & Hamilton 2002), enabling it to simulate a viscous, self-gravitating ring orbiting an oblate body. Our algorithm follows that used in the symplectic integrator epi_int (Hahn & Spitale 2013), in which the ring is simulated as many (~100) interacting, elliptic, confocal streamlines. This idea was first introduced in an analytic context by Goldreich & Tremaine (1979) and enabled rapid progress in the theory of ring evolution; since then, such discretization has been standard in the literature. While we adopt epi_int's streamline formalism, we nevertheless improve upon its design in several ways. Epi_int uses epicyclic elements in its drift step; approximating these elements introduces small, systematic errors that build up with time. We sidestep this problem by instead using the more traditional Keplerian osculating elements. In addition, epi_int uses several particles per wire to effectively calculate the inter-gravitational forces everywhere along each streamline. We replicate this ability but can often gain a speed boost by using a single tracer particle per streamline; while this restricts us to simulating rings dominated by the m = 1 mode, this is typical of most observed narrow eccentric ringlets. We have also extended epi_int's two dimensional algorithm into 3D. Finally, whereas epi_int is written in IDL, HNBody is written in C, which yields considerably faster integrations. Braga-Ribas et al. (2014) reported a set of narrow rings orbiting the Centaur Chariklo, but neither their investigation nor that of Pan & Wu (2016) yielded a satisfactory origin and evolution scenario. Eschewing the assumption that such rings must be short-lived, we instead argue (as in Rimlinger et al. 2016) that sufficiently eccentric rings can self-confine for hundreds of millions of years while circularizing. In this case, Chariklo may have formed rings as a KBO. We are working towards demonstrating both the feasibility of this theory and the utility of the HNBody extension by using it to simulate such a ring around Chariklo.

Kedron Silsbee, Princeton University

Forming a detached disk in the absence of external perturbations

One of the major puzzles in our solar system is the formation of the detached disk — a set of bodies with perihelia beyond the influence of Neptune, but aphelia too small to be affected by the Galactic environment. We investigate (via N-body simulations) a scenario in which the giant planets scatter multiple bodies with masses between that of Mars and the Earth, which are left over after the gas disk has dispersed. These bodies exert torques on one another while they are in the process of being ejected from the solar system. Thus, the perihelia of a few of these bodies are raised beyond the orbit of Neptune, so they no longer undergo substantial diffusion in semi-major axis, and remain

bound for the age of the solar system. These bodies also exert torques on smaller particles and place a few percent of the initial planetesimal disk into high-eccentricity, moderate inclination orbits with perihelia well outside of Neptune. The moderate inclinations of the observed scattered disk bodies are better reproduced in this model than one involving cluster tides or passing stars, which would be expected to produce a substantial number of retrograde bodies.

Juntai Shen, Shanghai Astronomical Obs.

Gas inflow patterns and nuclear rings in barred galaxies

Nuclear rings, dust lanes, and nuclear spirals are common structures in the inner region of barred galaxies, with their shapes and properties linked to the physical parameters of the galaxies. We use high-resolution hydrodynamical simulations to study gas inflow patterns in barred galaxies, with special attention on the nuclear rings. The location and thickness of nuclear ringsare tightly correlated with galactic properties, such as the bar pattern speed and bulge central density, within certain ranges. We identify the backbone of nuclear rings with a major orbital family of bars. The rings form exactly at the radius where the residual angular momentum of inflowing gas balances the centrifugal force. We propose a new simple method to predict the bar pattern speed for barred galaxies possessing a nuclear ring, without actually doing simulations. We apply this method to some real galaxies and find that our predicted bar pattern speed compare reasonably well with other estimates. Our study may have important implications for using nuclear ringsto measure the parameters of real barred galaxies with detailed gas kinematics. We have also extended current hydrodynamical simulations to model gas features in the Milky Way.

Altair Gomes, Observatório do Valongo

Predictions of Stellar Occultations by Irregular Satellites up to 2020

Due to their orbital configurations, it is believed the irregular satellites of the Giant Planets were captured by their host planets during the Solar System evolution. It is important to know their physical parameters such as size, shape, albedo and composition in an attempt to access their origin. The best ground-based technique to do so is by stellar occultations. With the release of the GAIA catalog and the publication of a large database of positions of irregular satellites (Gomes-Júnior et al., 2015), the position of the stars and the ephemeris of the satellites are improved to better predict stellar occultation. The present work predicts such events for the 8 largest irregular satellites of Jupiter and the largest irregular satellite of Saturn, Phoebe, up to 2020. Another motivation is the passage of Jupiter in front of the Galatic Plane in 2019-2020 increasing a lot the number of stars to be occulted. The same happens with Saturn in 2018.

Bruno Morgado, Observatório Nacional do Brasil

Astrometry of mutual approximations between the Galilean moons observed at 2016

A precise astrometry of natural satellites is very important to constrain dynamical models when taking into account week disturbances forces, such as tidal. For the Galilean moons of Jupiter, this astrometry is not an easy task, due to the brightness of Jupiter and its satellites. Usual CCD astrometry has a precision in the range of 100-120 mas. During the period of mutual phenomena, positions with a precision of a few mas can be obtained. However, mutual phenomena only happen during the equinox of the host planet, in the case of the Galilean moons every six years. This scenario motivates the development of alternatives methods to determine precise positions of these moons. One of these is the mutual approximations technique, in this method we determine the central instant in an apparent closest approach between two satellites. In this work, we determine the central instant of 50 curves observed from different observers. In total, 27 events were obtained, and 14 of those had at least two observers. All observations were made with a narrow-band filter centred at 889 nm with a width of 15 nm. The primary mirror of the telescopes ranges between 120-25 cm. The average precision obtained was 13 mas.

Elke Pilat-Lohinger, University of Vienna

Multi-Planets in Binary Star Systems

Space missions like Cheops, Tess or Plato will explore the solar neighborhood when searching for other Earth-like worlds. Moreover, observations have shown that many stars build binary or multi-stellar systems which might influence the dynamical behavior of planets moving in such systems where gravitational interactions play an important

role. Phenomena like mean motion resonances and secular resonances can be sources of both stability and instability and influence therefore the architecture of a planetary system significantly. In our solar system the two giant planets Jupiter and Saturn also influence the inner part of the planetary system. In this presentation we will show the dynamics of Jupiter-Saturn like configurations in binary stars and we analyse the changes in the dynamical behavior of the planets.

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