45th DDA Meeting

Philadelphia, PA – 28 April - 1 May 2014

Meeting Program With Abstracts

Session Table of Contents

Monday, 28 April 2014

Welcome Address, Matija Cuk, DDA Chair

Monday, 9:00 AM - 9:10 AM; Mitchell Hall

100 The Rich Dynamics of Planets in the Post-main-sequence Systems, Dimitri Veras (University of Warwick)

Monday, 9:10 AM - 9:50 AM; Mitchell Hall

100.01 The rich dynamics of planets in post-main-sequence systems

Mounting observations of ongoing and abundant ingestion of rocky and watery circumstellar material into white dwarf atmospheres have reinvigorated several subfields of dynamical astronomy. These observations demonstrate the importance of modeling planetary systems through the giant branch and white dwarf phases of stellar evolution. Consequently, dynamicists have renewed interest in the few-body problem with mass loss, tidal interactions of bloated stars, disrupted asteroids, sublimating accretion discs, and long-term stability analyses. Here, I outline these developments as well as remaining outstanding questions.

Author(s): ***Dimitri Veras (University of Warwick)***

101 Evolved Planetary Systems and Long Term Evolution

Monday, 9:50 AM - 10:30 AM; Mitchell Hall

101.01 Evolution of Planetary Orbits in Solar Systems with Stellar Mass Loss and Tidal Dissipation

Intermediate mass stars and stellar remnants often host planets, and these dynamical systems evolve due to mass loss and tides. This talk considers the combined action of stellar mass loss and tidal dissipation on planetary orbits and determines the conditions required for planetary survival. Stellar mass loss is included using a so-called Jeans model, described by a dimensionless mass loss rate γ and an index β. We use an analogous prescription to model tidal effects, described here by a dimensionless dissipation rate Γ and two indices (q,p). The initial conditions are determined by the starting value of angular momentum parameter η (equivalently, the initial eccentricity) and the phase θ of the orbit. Within the context of this model, we derive an analytic formula for the critical dissipation rate Γ, which marks the boundary between orbits that spiral outward due to stellar mass loss and those that spiral inward due to tidal dissipation. This analytic result $\Gamma = \Gamma(\gamma,\beta,q,p,\eta,\theta)$ is essentially exact for initially circular orbits and holds to within an accuracy of ~50% over the entire multi-dimensional parameter space, where the individual parameters vary by several orders of magnitude. For stars that experience mass loss, the stellar radius often displays quasi-periodic variations, which produce corresponding variations in tidal forcing; we generalize the calculation to include such pulsations using a semi-analytic treatment that holds to the same accuracy as the non-pulsating case. These results can be used in many applications, e.g., to predict/constrain properties of planetary systems orbiting white dwarfs.

Author(s): ***Fred Adams (University of Michigan)***, Anthony Bloch (University of Michigan)

101.02 The onset of large-scale dynamical instability in the Solar System

Over the last two decades, evidence has mounted that the centuries-old question concerning the dynamical stability of the solar system has a straight-forward, definitive answer: with a probability of ~1%, the inner solar system may gravitationally unravel on a timescale comparable to the remaining main-sequence lifetime of the Sun. Concurrently, as the orbital distribution of extrasolar planets began to surface, it had become clear that dynamical instability is a generic process that plays a central role in shaping the architecture of planetary systems. Despite its inherent significance, an unembellished qualitative description of the onset of orbital disorder is largely missing. In this work, we will describe a purely analytical theory for the chaotic disintegration of planetary systems. Specifically, with an emphasis on the Solar System, we will delineate a perturbative model that broadly captures the onset of large-scale instability and use it to elucidate the source of Mercury's chaotic behavior, as well as estimate the corresponding Lyapunov and diffusion coefficients. Subsequently, we will present a framework for calculating the characteristic dynamical lifetime of the inner Solar System. The obtained results constitute an important step towards developing an intuitive view of the long-term evolution of planetary systems.

Author(s): ***Konstantin Batygin (Harvard-Smithsonian Center for Astrophysics)***, Matthew Holman (Harvard-Smithsonian Center for Astrophysics), Alessandro Morbidelli (CNRS, OCA)

102 Planet Formation and Structure

Monday, 11:00 AM - 12:40 PM; Mitchell Hall

102.01 Forming Giant Planet Cores by Pebble Accretion -- Why Slow and Steady wins the Race

In recent years there has been a radical new solution proposed to solve the problem of giant planet core formation. "Pebbles", particles ranging from centimeters to meters in size, have been shown to accrete extremely efficiently due to aerodynamic drag. Large capture cross-sections combined with fast pebble drift rates can allow a single planetesimal to grow from Ceres size to 10s of Earth masses well within the lifetime of gaseous circumstellar disks. However, at large sizes, the the capture-cross section of pebbles goes with the Hill sphere, forcing pebble accretion to becomes a fundamentally "oligarchic-like" process. This makes it difficult to form a few giant planet cores; instead a more generic result is many 10s to 100s of competing oligarchs. In this work, we present a way to get around this oligarchic dilemma If pebbles are assumed to form slowly over a long period of time, then the planetesimal growth rates are slow enough for the planetesimals to dynamically excite each other. As the larger planetisimals/proto-planets stir their smaller companions, these smaller bodies are excited to such a degree that they spend only a small fraction of their orbits embedded in the cooler pebble disk. This allows the larger bodies to starve their neighbors and maintain a relative runaway growth rate to high mass, effectively forming the cores of giant planets.

Author(s): ***Katherine Kretke (Southwest Research Institute)***, Harold Levison (Southwest Research Institute)

102.02 Dynamical friction during planet formation in the Grand Tack scenario

It is well known that dynamical friction plays an important role during the last giant impact phase of terrestrial planet formation. We demonstrate not only how this mechanism determines the time of the last giant impact on the Earth but also the velocity and mass of giant impacts in general. These properties become important for understanding the divergent growth histories of Earth and Venus analogs. From these divergent histories, we can begin to build an explanation for the stark observed current-day differences between these two planets.

Author(s): ***Seth Jacobson (Observatoire de la Cote d'Azur)***, Alessandro Morbidelli (Observatoire de la Cote d'Azur)

102.03 Formation of the Terrestrial Planets from an Annulus

We present simulations that follow the growth process from km-sized objects up to terrestrial planets. We use a new Lagrangian code known as LIPAD (Levison, Duncan, and Thommes, 2012, AJ), which stands for 'Lagrangian Integrator for Planetary Accretion and Dynamics.' LIPAD is a particle-based code that models the fragmentation, accretion and dynamical evolution of a large number of planetesimals, and can model the entire growth process from km-sizes up to planets. The preliminary simulations explore a range of initial conditions where the solids in the disk are planetesimals with radii between 10 and 50 km, and the disk mass was varied from one to a few minimum mass solar nebula. The simulations were designed to examine the idea that some aspects of the terrestrial planets can be explained, particularly the Earth/Mars mass ratio, when they form from a truncated disk with an outer edge at 1.0 AU (Hansen 2009, Walsh et al. 2011). Therefore, we describe simulations that initially have planetesimals between 0.7--1.0 AU, and others that begin with material from 0.7--3.0 AU and were truncated at various times during the evolution of the disk. This work finds that planetesimals are depleted rapidly due to collisional fragmentation, an effect that is amplified when the disk is truncated by the migration of giant planets. The mass distribution of the planets is not well matched for simulations starting as an annulus, and better matches are found for disks truncated at later times. We discuss other similarities and differences with previous models of terrestrial planet formation.

Author(s): ***Kevin Walsh (Southwest Research Institute)***, Harold Levison (Southwest Research Institute)

102.04 Theia's Provenance: Regional Source of Earth's Late Impactor

In the Solar System's early history many processes have been proposed that depend on the dynamical state of the planets. Our study considers the possible dynamical states during the late stage of accretion that produce a late Giant Impact (60 – 120 Myr after CAIs) to form the Earth-Moon system. We investigate within the semimajor axis and eccentricity parameter space the possible outcomes of a 5 terrestrial planet model of the Solar System for 3 different mass ratios (8:1, 4:1, and 1:1) of the Earth-Moon progenitors. Using angular momentum conservation, an initial condition is prescribed for the progenitor masses while utilizing initial conditions for the other Solar System bodies from a well-known common epoch. Additionally we test the 4:1 mass ratio with a different giant planet configuration akin to the Nice model. We find local regions of our parameter space are more conducive to the outcome of a late Giant Impact between the intended progenitors. Mean motion resonances (MMRs) are identified between the terrestrial planets and used, along with secular effects from the giant planets, to indicate likely regions of initial conditions that result in a Giant Impact. We further characterize our results considering the estimated time of the Giant Impact, the resultant mass distribution of terrestrial planets, and the post collision 10 Myr mean angular momentum deficit (AMD). Case studies are presented illustrating the various possible outcomes and mechanisms with respect to their AMD relative to the current Solar System. Our statistical results show that a Nice model giant planet configuration can affect the occurrence of Giant Impacts for certain regions of the parameter space. The implications on planet formation scenarios and implicit habitability will also be discussed.

Author(s): ***Billy Quarles (NASA Ames Research Center)***, Jack Lissauer (NASA Ames Research Center)

102.05 Tidal dissipation in the dense anelastic core of giant planets

The prescriptions used today in celestial mechanics to describe dynamical processes, such as tidal interactions, are somewhat crude. In particular, the quality factor Q, quantifying the tidal dissipation, is often taken as constant, despite its dependence on internal structure, and thus on the tidal frequency. In a solid layer, Efroimsky & Lainey (2007) showed the importance of using a realistic prescription of Q to estimate the evolution speed of the Mars-Phobos system. Such studies confirm the necessity to go beyond evolution models using ad-hoc Q values. Recent astrometric observations of the dynamical evolution of the Jovian and Saturnian systems have shown a higher tidal dissipation than expected (for Jupiter: Q≈3.6×10^3, and for Saturn: Q≈1.7×10^3, from Lainey et al. 2009,2012 resp.). According to a recent model of the Saturnian system formation, such a high tidal dissipation is required by the satellites to migrate up to their present location over the age of the solar system (Charnoz et al., 2011). Globally, gas giants are constituted by a large fluid envelope and a dense central icy/rocky core (Hubbard & Marley 1989). Fluid models, where the tide excites the inertial waves of the convective envelope, show that the resulting tidal dissipation is of the order of Q≈10^5-10^7 (Wu 2005, Ogilvie & Lin 2004). These models have neglected the possible dissipation by the core. Thus, we have developed a model evaluating the tidal dissipation in the anelastic central region of a two-layer planet, surrounded by a static envelope, tidally excited by the hostingstar or a satellite (Remus et al., 2012). The tide exerted by the companion deforms both the envelope and the core. Because of its anelasticity, the core also creates tidal dissipation. I will discuss how the tidal dissipation depends on the rheological parameters and the size of the core. Assuming realistic models of internal structure and taking into account the frequency dependence of the solid dissipation, I will show how this mechanism might compete with the dissipation in fluid layers, and even explain the observed values of tidal dissipation. [abridged]

103 The Solar System

Monday, 2:00 PM - 4:00 PM; Mitchell Hall

103.01 The Trajectory of the Chelyabinsk Impactor

On February 15, 2013, a small asteroid called 2012 DA14 was about to make a much anticipated extremely close flyby of the Earth, when an even smaller asteroid stole the show by impacting into the Earth's atmosphere near Chelyabinsk, Russia, releasing half a megaton of energy and creating a shock wave that reportedly injured more than a thousand people. The passage of a 40-meter asteroid within the ring of geosynchrounous satellites is rare, calculated to be a once-in-40-year event, and yet it was upstaged on the same day by an actual Earth impact of a previously unseen 20-meter asteroid, an event expected to occur only about once per century, on average. Infrasound-based estimates of the released energy from this impact lie in the range of from 450 to 700 kilotons, making the Chelyabinsk fireball the largest impact event since the Tunguska explosion over Siberia in 1908. We have analyzed the approach trajectory of the impactor using impact event data provide U.S. Government sensors. We compare our results with other more detailed analyses of the trajectory. All of the analyses indicate that the asteroid approached the Earth from within 20 degrees of the sunline. Clearly, this object could not have been detected on its final approach by any of the asteroid search programs, unlike the even smaller asteroid 2008 TC3, which was discovered as it approached the Earth from near the opposition point. It is also clear that the east-to-west trajectory of the Chelyabinsk impactor was very different from the south-to-north path of 2012 DA14, implying that the two asteroids were unrelated.

Author(s): ***Paul Chodas (JPL/Caltech)***, Steven Chesley (JPL/Caltech)

103.02 Trajectory and physical properties of near-Earth asteroid 2009 BD

We analyze the trajectory of near-Earth asteroid 2009 BD, which is a candidate target of the NASA Asteroid Robotic Retrieval Mission (ARRM). The small size of 2009 BD and its Earth-like orbit pose challenges to understanding the dynamical properties of 2009 BD. In particular, nongravitational perturbations, such as solar radiation pressure and the Yarkovsky effect, are essential to match observational data and provide reliable predictions. By using Spitzer Space Telescope IRAC observations and our estimates of the nongravitational forces acting on 2009 BD we obtain probabilistic derivations of the physical properties of this object. We find two physically possible solutions. The first solution shows 2009 BD as a 2.9±0.3 m diameter rocky body with an extremely high albedo that is covered with regolith-like material, causing it to exhibit a low thermal inertia. The second solution suggests 2009 BD to be a 4±1 m diameter asteroid with albedo 0.45±0.35 that consists of a collection of individual bare rock slabs. We are unable to rule out either solution based on physical reasoning. 2009 BD is among the smallest asteroids for which physical properties have been constrained, providing unique information on the physical properties of objects in the size range smaller than 10 m.

Author(s): ***Steven Chesley (Jet Propulsion Laboratory, California Institute of Technology)***, Michael Mommert (Northern Arizona University), Joseph Hora (Harvard-Smithsonian Center for Astrophysics), Davide Farnocchia (Jet Propulsion Laboratory, California Institute of Technology), David Trilling (Northern Arizona University), David Vokrouhlický (Charles University), Michael Mueller (SRON Netherlands Institute for Space Research), Alan Harris (DLR Institute of Planetary Research), Howard Smith (Harvard-Smithsonian Center for Astrophysics), Giovanni Fazio (Harvard-Smithsonian Center for Astrophysics)

103.03 Enhancement of the natural Earth satellite population through meteoroid aerocapture

The vast majority of meteoroids either fall to the ground as meteorites or ablate completely in the atmosphere. However, large meteoroids have been observed to pass through the atmosphere and reenter space in a few instances. These atmosphere-grazing meteoroids have been characterized using ground-based observation and satellite-based infrared detection. As these methods become more sensitive, smaller atmosphere-grazing meteoroids will likely be detected. In anticipation of this increased detection rate, we compute the frequency with which centimeter-sized meteoroids graze and exit Earth’s atmosphere. We characterize the post-atmosphere orbital characteristics of these bodies and conduct numerical simulations of their orbital evolution under the perturbing influence of the Sun and Moon. We find that a small subset of aerocaptured meteoroids are perturbed away from immediate atmospheric reentry and become temporary natural Earth satellites.

Author(s): ***Althea Moorhead (NASA Meteoroid Environment Office)***, William Cooke (NASA Meteoroid Environment Office)

103.04 Trajectory analysis for the nucleus and dust of comet C/2013 A1 (Siding Spring)

Comet C/2013 A1 is going to experience a close encounter with Mars on Oct 19, 2014 at a distance of 135,000 km ± 5000 km from the planet center. Because of its near parabolic retrograde orbit, C/2013 A1 has a high relative velocity with respect to Mars of about 56 km/s. There is increasing interest in analyzing the close encounter both for the comet nucleus and the dust tail. We analyze the nucleus trajectory and model the contribution of nongravitational forces, which can significantly affect comet dynamics. Since the astrometry does not yet provide any constraint on nongravitational accelerations, our analysis relies on what we know of the whole comet population. It turns out that the nucleus cannot reach Mars even in the case of unexpected large nongravitational perturbations. On the other hand, dust released because of cometary activity can reach Mars if the emission velocity is large enough. For given size and density of the emitted dust particles we compute the required emission velocity needed to reach Mars as a function of emission epoch. Comparing our results to the current modeling of C/2013 A1's cometary activity suggests that impacts are possible only for millimeter to centimeter size particles released more than 20 au from the Sun. However, cometary activity that far from the Sun is considered extremely unlikely. Ejection velocity larger than currently modeled could allow dust particles to reach Mars if ejected more than 3 au form the Sun. In this case the impact times peak around 100 min after the nominal close approach around the time that Mars crosses C/2013 A1's orbital plane.

Author(s): ***Davide Farnocchia (JPL, Caltech)***, Steven Chesley (JPL, Caltech), Paul Chodas (JPL, Caltech)

103.05 Binary Near-Earth Asteroids: Satellite Spin States Under Spin-Orbit Coupling

We numerically investigated the effects of spin-orbit coupling on the spin states of satellites in binary Near-Earth Asteroid (NEA) systems. For these simulations, we integrated the equations of motions in the primary body-fixed reference frame, as derived by Maciejewsky 1995. We computed forces and torques on the components by taking derivatives of the mutual potential between the two bodies expressed in terms of their inertia integrals expanded to fourth degree (Ashenberg 2007). The integrator is capable of handling arbitrary shapes, mass distributions, and non-planar configurations, which is more general than the formalism of McMahon & Scheeres 2013. The spin angular momentum of secondaries in binary NEAs amounts to a non-negligible fraction of the system’s angular momentum budget (Margot et al. 2002, Ostro et al. 2006), and it has been suggested that the mutual orbits and secondary spins are highly coupled, affecting the onset of Hyperion-like chaos (Wisdom et al 1984). We explored the phase space with our coupled spin-orbit integrator, and we identified regions of regular and chaotic motion on Poincaré maps. Even regular cases result in large libration amplitudes and large spin-rate variations. These have implications for the strength of binary YORP, which is hypothesized to modify orbits of synchronous satellites on rapid timescales (McMahon & Scheeres 2010, Cuk & Nesvorny 2010). These spin-rate variations are also important for interpreting radar data, as the Doppler widths are spin-rate-dependent. About 50 binary NEAs are known but less than a dozen have well-determined mutual orbital parameters (semimajor axes and

104 My Chaotic Trajectory: A Brief (personalized) History of Solar-System Dynamics, Joseph Burns (Cornell University)

Monday, 4:00 PM - 4:40 PM; Mitchell Hall

104.01 My chaotic trajectory: A brief (personalized) history of solar-system dynamics.

I will use this opportunity to recall my professional career. Like many, I was drawn into the space program during the mid-60s and early 70s when the solar system's true nature was being revealed. Previously, dynamical astronomy discussed the short-term, predictable motions of point masses; simultaneously, small objects (e.g., satellites, asteroids, dust) were thought boring rather than dynamically rich. Many of today's most active research subjects were unknown: TNOs, planetary rings, exoplanets and debris disks. The continuing stream of startling findings by spacecraft, ground-based surveys and numerical simulations forced a renaissance in celestial mechanics, incorporating new dynamical paradigms and additional physics (e.g., energy loss, catastrophic events, radiation forces). My interests evolved as the space program expanded outward: dust, asteroids, natural satellites, rings; rotations, orbital evolution, origins. Fortunately for me, in the early days, elementary models with simple solutions were often adequate to gain a first-order explanation of many puzzles. One could be a generalist, always learning new things. My choice of research subjects was influenced greatly by: i) Cornell colleagues involved in space missions who shared results: the surprising diversity of planetary satellites, the unanticipated orbital and rotational dynamics of asteroids, the chaotic histories of solar system bodies, the non-intuitive behavior of dust and planetary rings, irregular satellites. ii) Teaching introductory courses in applied math, dynamics and planetary science encouraged understandable models. iii) The stimulation of new ideas owing to service at Icarus and on space policy forums. iv) Most importantly, excellent students and colleagues who pushed me into new research directions, and who then stimulated and educated me about those topics. If time allows, I will describe some of today's puzzles for me and point out similarities between the past development in our understanding of the solar system's operation and the contemporary quest to figure out exoplanet systems.

Author(s): ***Joseph Burns (Cornell Univ.)***

Tuesday, 29 April 2014

200 Circumbinary Planetary Systems at Home and Abroad, Kaitlin Kratter (University of Arizona)

Tuesday, 9:00 AM - 9:40 AM; Mitchell Hall

200.01 Circumbinary Planetary Systems at Home and Abroad

The Kepler mission has revealed a new class of (main-sequence) planetary system: circumbinaries. In these systems, a tight binary is orbited by one or more planets. From a dynamical perspective, these systems are not new, but rather a scaled up version of the Pluto-Charon system. In this talk I will discuss what we can learn from a detailed study of the dynamics of both Pluto-Charon and Kepler circumbinary systems. I will describe how circumbinary planets may be crucial for our understanding of binary star formation, and why these unique systems may be excellent places to search for habitable zone planets.

Author(s): ***Kaitlin Kratter (University of Arizona)***, Andrew Shannon (IoA Cambridge), Andrew Youdin (University of Arizona), Scott Kenyon (Harvard-Smithsonian CfA)

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201 Exoplanets 1

Tuesday, 9:40 AM - 10:40 AM; Mitchell Hall

201.01 Joint Bayesian and N-body Analyses of the 55 Cancri and GJ 876 Planetary Systems

We present the latest dynamical models for the 55 Cancri and GJ 876 systems based on 1,418 and 367 radial velocity (RV) observations, respectively. We apply our Radial velocity Using N-body Differential evolution Markov chain Monte Carlo code (RUN DMC; B. Nelson et al. 2014) to these two landmark systems and perform long-term (~10^8 year) dynamical integrations using the Mercury symplectic integrator. For 55 Cancri, we find the transiting planet "e" cannot be misaligned with the outer four planets by more than 60 degrees and has a relativistic precession timescale on the order of the secular interactions. Based on a statistical analysis, we conclude planets "b" and "c" are apsidally aligned about 180 degrees but not in a mean-motion resonance. For GJ 876, we derive a set of 3-dimensional (non-coplanar) dynamical models based solely on RVs.

Author(s): ***Benjamin Nelson (Pennsylvania State University, Center of Exoplanets and Habitable Worlds)***, Eric Ford (Pennsylvania State University, Center of Exoplanets and Habitable Worlds), Jason Wright (Pennsylvania State University, Center of Exoplanets and Habitable Worlds), Debra Fischer (Yale University)

201.02 Measuring the masses, radii and orbital eccentricities of sub-Neptunes with transit timing variations.

Outside our solar system, there is a small sample of planets with known masses and radii, mostly hot jupiters whose radii are known from transit depths, and whose masses are determined from radial velocity spectroscopy (RV). In the absence of mass determinations via RV observations, transit timing variations (TTVs) offer a chance to probe perturbations between planets that pass close to one another or are near resonance, and hence dynamical fits to observed transit times can measure planetary masses and orbital parameters. Such modeling can probe planetary masses at longer orbital periods than RV targets, although not without some challenges. For example, in modeling pairwise planetary perturbations near first order mean motion resonances, a degeneracy between eccentricity and mass exists that limits the accuracy of mass determinations. Nevertheless, in several compact multiplanet systems, fitting complex TTV signals can break the degeneracy, permitting useful mass constraints, and precise measures of small but non-zero eccentricity. The precision in measuring the radius of a transiting planet rests on the uncertainty in the stellar radius, which is typically ~10% for targets with spectral follow-up. With dynamical fits, however, solutions for the orbital parameters including the eccentricity vectors can, alongside the transit light curves, tightly constrain the stellar density and radius. Alongside spectroscopic data, our dynamical fits to TTVs reduced the stellar and hence planetary radius uncertainties at Kepler-11 and Kepler-79 to just 2%, permitting useful planetary density determinations. In the case of Kepler-79, planetary bulk densities are remarkably low given the planetary masses. Indeed, several multiplanet systems characterized by TTV show much lower planetary densities than typical RV determinations in the same mass range. While this reflects the detection biases of both techniques, it also represents a growing sample of characterized systems of multiple planets, whose low densities and compact configurations provide a striking contrast to the Solar System.

Author(s): ***Daniel Jontof-Hutter (NASA Ames Research Center)***, Jack Lissauer (NASA Ames Research Center), Jason Rowe (NASA Ames Research Center, SETI Institute), Daniel Fabrycky (University of Chicago)

201.03 Scattering outcomes of close-in planets

Many exoplanets in close-in orbits are observed to have relatively high eccentricities and large stellar obliquities. We explore the possibility that these result from planet-planet scattering by studying the dynamical outcomes from a large number of orbit integrations in systems with two and three gas-giant planets in close-in orbits (0.05 AU< a <0.15 AU). We find that at these orbital separations, unstable systems generally lead to planet-planet collisions in which the collision product is a planet on a low-eccentricity, low-inclination orbit. This result is inconsistent with the observations. We conclude that eccentricity and inclination excitation from planet-planet scattering must precede migration of planets into short-period orbits.

Author(s): ***Cristobal Petrovich (Princeton University)***, Scott Tremaine (Institute for Advanced Study), Roman Rafikov (Princeton University)

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202 Exoplanets 2

Tuesday, 11:00 AM - 12:40 PM; Mitchell Hall

202.01 Tidal Synchronization of Close-in Satellites and Exoplanets, Host Stars and Mercury

This paper deals with an application of the creep tide theory (Ferraz-Mello, Cel. Mech. Dyn. Astron. 116, 109, 2013) to the rotation of close-in satellites, Mercury, close-in exoplanets and their host stars. The solutions show different behaviors in the two extreme cases: low-viscosity close-in gaseous planets and stars (high relaxation factor) and high-viscosity rocky satellites and planets (low relaxation factor). The rotation of close-in gaseous planets follows the classical Darwinian pattern: it is tidally driven towards a synchronous solution when the orbit is circular, but to a super-synchronous solution, with frequency (1+6e^2) times the orbital mean-motion, when the orbit is elliptic. The rotation of rocky bodies, however, may be driven to several attractors whose frequencies are 1/2, 1, 3/2, 2, 5/2,… times the mean-motion. The number of attractors increases with the viscosity of the body and the orbital eccentricity. The final stationary state depends on the initial conditions and on the eccentricity of the orbits. The well-known case of Mercury, whose rotational period is 2/3 of the orbital period (3/2 attractor), is a consequence of the nonzero orbital eccentricity and of the relaxation factor of the planet (large enough to avoid the 2/1 attractor, but small enough to be trapped in the 3/2 one). Mercury's relaxation factor can thus be estimated to lie in the interval 4.6−27 nHz (which allows Q to be roughly constrained to the interval 5<Q<50). The stars behave as the hot Jupiters – they have similar relaxation factors – and their rotation is driven to the near synchronous attractor. However, stellar activity also affects the rotation displacing the stationary solution towards smaller frequencies; a host star with big close-in companion is expected to have its rotational period larger than the orbital period of the companion (i.e. sub-synchronous). It is worth stressing that in all studied cases, the stationary solutions were direct consequences of the creep tide; the possible presence of a fossil or permanent triaxiality has not yet been included in the approach.

Author(s): ***Sylvio Ferraz-Mello (IAG-USP)***

202.02 Chaotic Dynamics of Stellar Spin in Binaries and the Production of Misaligned Hot Jupiters

Secular Kozai oscillation, induced by a distant stellar companion and acting in concert with tidal dissipation, is one of the major channels for the production of hot Jupiters (extrasolar gas giants in 1-5 day orbits) and close stellar binaries. This mechanism is particularly attractive due to the high degree of misalignment between the stellar spin and planet/binary orbital angular momentum axes that has been observed in many systems. In the typical Kozai picture, this misalignment is thought to be the result of large variation in the planet’s orbital axis, while the stellar spin orientation remains mostly fixed. Here we demonstrate that gravitational interaction between the stellar spin and the planetary orbit can induce a variety of dynamical behaviors for the stellar spin evolution during the Kozai cycle. In particular, in systems hosting giant planets, the stellar spin exhibits rich, often strongly chaotic dynamics, with Lyapunov times as short as 10 Myr. This arises from secular spin-orbit resonances and resonance overlaps. We construct Poincare surfaces of section to demonstrate the chaotic behavior. As the system parameters (such as planet mass) vary, “periodic islands” can appear in largely chaotic domains, in a manner reminiscent of the logistic map or Lorenz chaos. We show that in the presence of tidal dissipation, the memory of chaotic spin evolution can be preserved, leaving an imprint on the final spin-orbit misalignment angles.

Author(s): ***Natalia Storch (Cornell University)***, Kassandra Anderson (Cornell University), Dong Lai (Cornell University)

202.03 Chaotic Dynamics of Stellar Spin in Binaries and the Production of Misaligned Hot Jupiters. Part II

Secular Kozai oscillations, induced by a distant stellar companion and acting in concert with tidal dissipation, is one of the major channels for the production of hot Jupiters (extrasolar gas giants in 1-5 day orbits) and close stellar binaries. This mechanism is particularly attractive due to the high degree of misalignment between the stellar spin and planet/binary orbital angular momentum axes that has been observed in many systems. In the typical Kozai picture, this misalignment is thought to be the result of large variation in the planet's orbital axis, while the stellar spin orientation remains mostly fixed. Here we demonstrate that gravitational interaction between the stellar spin and the planetary orbit can induce a variety of dynamical behaviors for the stellar spin evolution during the Kozai cycle. In particular, in systems hosting giant planets, the stellar spin exhibits rich, often strongly chaotic dynamics, with Lyapunov times as short as 10~Myr. This arises from secular spin-orbit resonances and resonance overlaps. We construct Poincar\'{e} surfaces of section to demonstrate the chaotic behavior. As the system parameters (such as planet mass) vary, ``periodic islands'' can appear in largely chaotic domains, in a manner reminiscent of the logistic map or Lorenz chaos. We show that in the presence of tidal dissipation, the memory of chaotic spin evolution can be preserved, leaving an imprint on the final spin-orbit misalignment angles.

Author(s): ***Kassandra Anderson (Cornell University)***, Natalia Storch (Cornell University), Dong Lai (Cornell University)

202.04 Fine Structure in the Architectures of Kepler Systems

Kepler's multiplanet systems allow unprecedented insights into the architectures and dynamics of the inner parts of planetary systems. I present the results of recent investigations into some of the details of Kepler system architectures. Of particular interest are statistically significant dependence of the period ratio of planet pairs on both the number of planets observed in a system and on the orbital distance of that pair from their host star. Each of these observations indicate some difference in either the formation history or the dynamical evolution of these systems.

Author(s): ***Jason Steffen (Northwestern University)***

202.05 Planetesimal Interactions Explain the Mysterious Period Ratio Distribution Near Mean Motion Resonances

One of the most intriguing trends among the Kepler multi-planet systems is a clear over abundance of planet pairs with period ratios just wide of several mean motion resonances (MMR) and a dearth of systems just narrow and with exact integer ratios corresponding to these MMRs. This is in dramatic contrast to the period ratio distribution of multi-planet systems discovered via radial velocity (RV) surveys where planet pairs tend to pile up near exact integer ratio of orbital periods such as 2/1. We will show how Interactions between a planetesimal disk and planet pairs in MMR can naturally explain all of the observed trends for large ranges in planet and planetesimal disk properties.

Author(s): ***Sourav Chatterjee (University of Florida)***, Eric Ford (Penn State University)

203 Dynamical and Kinematic Stucture of Bars with Supermassive Black Holes, Monica Valluri (University of Michigan)

Tuesday, 2:00 PM - 2:40 PM; Mitchell Hall

203.01 Dynamical and Kinematic Structure of Bars with Supermassive Black Holes

Observational studies have shown that nearly 65% of disk galaxies in the local Universe are barred. Furthermore, there is evidence that nearly every galaxy with a substantial central light concentration contains a supermassive black hole. This implies that bars frequently (or perhaps always) co-exist with supermassive black holes. Our recent studies have shown that the dynamical influence of a bar (e.g. its ability to transport angular momentum) and its orbital structure alters the observable kinematics in galactic nuclei. I will describe independent yet complementary sets of simulations that show that the effect of a bar is to increase the velocity dispersion within the effective radius on average by between 7% and 12% depending on when the black hole forms relative to the formation of the bar. This predicted effect is somewhat less than previous claims of the offset observed in data. Our investigations of the orbital structure of N-body bars (using automated orbit classification methods that rely on orbital spectral analysis) show that their self-consistent distribution functions comprise significantly fewer varieties of orbits than have previously been found in analytic bar potentials. The principle orbit families of N-body bars bear surprising similarity to those of slowly rotating triaxial potentials. Finally, the presence of a galactic bar can result in an overestimate of the stellar dynamical measurement of the black hole mass. I will present a new stellar dynamical model for the nucleus of the galaxy NGC 4151 which illustrates some of the problems associated with measuring the black hole mass in this barred Seyfert I galaxy.

Author(s): ***Monica Valluri (University of Michigan)***

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204 Galaxies and Galactic Structure

Tuesday, 2:40 PM - 3:40 PM; Mitchell Hall

204.01 Smoothing Rotation Curves in Spiral Galaxies

We present evidence that spiral activity is responsible for the creation of featureless rotation curves. We examine a variety of simulations of disk galaxies beginning in equilibrium and allow them to evolve while adding particles in annuli to the hot disk using a variety of rules. Two unstable spiral modes develop when this new material forms a ridge-like feature in the surface density profile of the disk. The extra material is redistributed radially by the spiral activity, and the associated angular momentum changes remove more particles from the ridge than are added to it. This process eventually removes the density feature from the galaxy and creates a locally flat rotation curve. We argue that the lack of a feature when transitioning from disk to halo dominance in the rotation curves of disk galaxies, the so called ``disk-halo conspiracy'', could also be accounted for by this mechanism.

Author(s): ***Joel Berrier (Rutgers University)***, Jerry Sellwood (Rutgers University)

204.02 GALAXY - a highly efficient, collisionless N-body simulation code

After decades of development, I am making this N-body simulation code publicly available. The code calculates the gravitational field on grids having a number of different possible geometries. Because there are many fewer grid points than particles, the execution speed is orders of magnitude higher than for tree codes, enabling large numbers of particles to be employed with modest computational resources. Speed comes at the cost of reduced flexibility; in particular, the code is unsuited to problems with many density concentrations. I will give a brief description of the method and its performance, and illustrate the quality of results it can achieve.

Author(s): ***Jerry Sellwood (Rutgers Univ.)***

204.03 Dynamics of the Milky Way Bulge and its X-shaped Structure

Bulges are commonly believed to form in the dynamical violence of galaxy collisions and mergers. We model the stellar kinematics of the Bulge Radial Velocity Assay (BRAVA) and find no sign that the Milky Way contains a classical bulge formed by scrambling pre-existing disks of stars in major mergers. Rather, the bulge appears to be a bar seen somewhat end-on, as hinted from its asymmetric boxy shape. We construct a simple but realistic N-body model of the Galaxy that self-consistently develops a bar. The bar immediately buckles and thickens in the vertical direction. As seen from the Sun, the result resembles the boxy bulge of our Galaxy. The model matches the BRAVA stellar kinematic data covering the whole bulge strikingly well with no need for a merger-made classical bulge. Our model contains an intriguing vertical X-shaped structure that resembles the similar structure reported recently in the Galactic bulge. We discuss the properties and current understanding of the X-shaped bulge. The existence of the vertical X-shaped structure also suggests that the formation of the Milky Way bulge is shaped mainly by internal disk dynamical instabilities.

Author(s): ***Juntai Shen (Shanghai Astronomical Obs.)***

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205 Other Dynamical Topics

Tuesday, 4:00 PM - 5:00 PM; Mitchell Hall

205.01 Tides, Planetary Companions, and Habitability

Earth-scale planets in the classical habitable zone (HZ) are more likely to be habitable if they possess active geophysics to drive processes that regulate their atmosphere. Without a constant internal energy source, planets cool as they age, eventually terminating tectonic activity. Planets orbiting low-mass stars can be very old, due to the longevity of such stars, so they may be rendered sterile to life in this way. However, the presence of an outer companion could generate enough tidal heat in the HZ planet to prevent such cooling. The range of mass and orbital parameters for the companion that give adequate long-term heating of the inner HZ planet, while avoiding very early total desiccation, is substantial. We locate the ideal location for the outer of a pair of planets, under the assumption that the inner planet has the same incident flux as Earth, orbiting example stars: a generic late M dwarf and the M9V/L0 dwarf DEN1048. We also analyze the extent to which systems with ideal parameters for heating will evolve over time. Thus discoveries of Earth-scale planets in the HZ zone of old small stars should be followed by searches for outer companion planets that might be essential for current habitability.

Author(s): ***Christa Van Laerhoven (University of Arizona)***, Rory Barnes (University of Washington), Richard Greenberg (University of Arizona)

205.02 Dynamical Behavior of Ejecta Produced by the Proposed ISIS Kinetic Impactor Demonstration

Impactor for Surface and Interior Science (ISIS) is a proposed mission of opportunity that would demonstrate and test kinetic impact (KI) for orbit modification of a hypothetical NEO to reduce its Earth impact probability. Unlike Deep Impact, this test entails measuring ΔV imparted to a far smaller asteroidal target body (Bennu) using another spacecraft in rendezvous with that body both before and after the KI event (OSIRIX-REx). To quantify any hazard to OSIRIS-REx from collision with liberated ejecta, we perform detailed study of the ejecta's dynamical behavior. For KI event energy matching a 440 kg impactor at 13.43 km/s closing velocity, we model crater formation and ejecta generation consistent with the small net surface acceleration in the targeted equatorial region of the sunlit hemisphere at the February 2021 impact epoch, and reasonable material strength for such a low-density rubble-pile. A crater ≈25 m in diameter is excavated over several minutes, liberating several thousand metric tons of material, with maximum velocity ≈34 m/s. We propagate ejecta under all relevant dynamical effects, including shape-model-derived full body gravity, differential solar tide acceleration, and solar radiation pressure (SRP) accounting for realistic particle size-frequency distribution, optical properties, and shadowing. We present the proportion of particles reaching the dynamical fates of return impact or exit from the region of importance to OSIRIS-REx operations, vs. time. We show where the re-accreted ejecta deposits on the surface, and the size-frequency distribution of the population remaining at 1, 5, 10, etc. days post-impact. We find clearing times from the system are nonlinearly dependent on particle size as expected, especially for low-velocity ejecta which stream away anti-sunward under the action of SRP within a paraboloid zone. Higher-velocity ejecta persist for longer durations within a sunward extension of the original ejecta cone. We visualize spatial density and flux of several relevant quantities (number, mass, collision momentum, collision kinetic energy) on the way to similar visualization of time-integrated probability of a particle collision with kinetic energy above a damaging threshold.

Author(s): ***Eugene Fahnestock (Jet Propulsion Laboratory, California Institute of Technology)***, Steven Chesley (Jet Propulsion Laboratory, California Institute of Technology), Davide Farnocchia (Jet Propulsion Laboratory, California Institute of Technology)

205.03 On the post mitigation impact risk assessment of possible targets for an asteroid deflection demonstration mission in the NEOShield project.

Mankind believes to have the capabilities to avert potentially disastrous asteroid impacts. Yet, only the realization of a mitigation demonstration mission can confirm such a claim. The NEOShield project, an international collaboration under European leadership, aims to draw a comprehensive picture of the scientific as well as technical requirements to such an endeavor. One of the top priorities of such a demonstration mission is, of course, that a previously harmless target asteroid shall not be turned into a potentially hazardous object. Given the inherently large uncertainties in an asteroid's physical parameters, as well as the additional uncertainties introduced during the deflection attempt, an in depth analysis of the change in asteroid impact probabilities after a deflection event becomes necessary. We present a post mitigation impact risk analysis of a list of potential deflection test missions and discuss the influence of orbital, physical and mitigation induced uncertainties.

Author(s): ***Siegfried Eggl (IMCCE - Observatoire de Paris)***

Wednesday, 30 April 2014

300 Classical Topics

Wednesday, 9:00 AM - 9:40 AM; Mitchell Hall

300.01 Tidal dissipation in a homogeneous spherical body. Revisiting the old problem.

A formula for the tidal dissipation rate in a spherical body is derived from first principles, to correct some mathematical inaccuracies found in the literature. The development is combined with the Darwin-Kaula formalism for tides. Our intermediate results are compared with those by Zschau (1978) and Platzman (1984). When restricted to the special case of an incompressible spherical planet spinning synchronously without libration, our final formula can be compared with the commonly used expression from Peale & Cassen (1978, Eqn. 31). The two turn out to differ. While in our expression the contributions from all Fourier modes are positive-definite, this is not the case of the formula from Ibid. As a result of this, the formula by Peale & Cassen (1978) may in some situations result in underestimation of tidal heat production. Simplified formulae for dissipation rate, in the case of Maxwell rheology, are derived for synchronous and asynchronous rocky planets. Three case studies are presented: Mercury, the enigmatic Kepler-10b, and a triaxial Io. A very sharp frequency-dependence of k_2/Q near resonances yields a similarly sharp dependence of k_2/Q on the spin rate. This compels us to hypothesise that physical libration and, therefore, the triaxiality play a major role in tidal heating.

Author(s): ***Michael Efroimsky (U.S. Naval Observatory)***, Valeri Makarov (U.S. Naval Observatory)

300.02 When Did the Mean Solar Day Equal 86,400 SI Seconds?

The "mean solar day" is the time for one Earth rotation with respect to the mean Sun. The goal of this talk is to show that the mean solar day, measured at the ms level with atomic clocks, both increases and decreases. The exposition speaks to the occasional controversy over the non-uniform rate at which leap-seconds are inserted into the time disseminated by national time services to compensate for varying Earth rotation. The controversy often centers on the "equality question": "When did the mean solar day equal 86,400 SI seconds?" Systeme International (SI) seconds are the seconds told by atomic clocks. Tidal friction lengthens the mean solar day by ~2 ms/cy when measured on an Atomic timescale. With this lengthening in mind, the answer commonly given is that mean solar day equality occurred in the year ~1820, but this answer fails to account that at the ms level, spin torques from the non-dissipative component of Earth body tides and from changes in Atmospheric Angular Momentum can increase and decrease the mean solar day by amounts greater than the lengthening from tidal friction acting over 1 cy. The result is that mean solar day equality has occurred on multiple occasions. For example, VLBI data show that Earth body tides brought the mean solar day through 86,400 SI seconds on 6 different dates in the year 2009. If we remove the effects of body tides and look at yearly averages, in the 20th century the mean solar day was 86,400 SI seconds at 6 different times through the years 1927-1935. There were also numerous occurrences during the 19th century. The changed answers proposed here are conceptually interesting, but they do not imply any actual error in past determinations of Earth rotation phase on Atomic timescales (the International Atomic Time/Universal Time difference).

Author(s): ***Victor Slabinski (U.S. Naval Observatory)***

301 The Solar System: Titan

Wednesday, 9:40 AM - 11:00 AM; Mitchell Hall

301.01 Recent Origin of Titan's Orbital Eccentricity

Saturn's regular satellite system contains several dynamical mysteries, including the high tidal heating of Enceladus and undamped eccentricity of Titan. Lainey et al.(2012) proposed that the tidal evolution of the system is much faster than previously thought, which would explain heating of Enceladus and implies that some of the current satellites are less than 1 Gyr old. Cuk et al.(2014) pointed out that this fast tidal evolution could also explain the Titan-Hyperion resonance. If the inner, mid-sized Saturnian moons were re-accreted within the last Gyr, then the same event could have generated the observed eccentricity of Titan. Titan-Hyperion resonance puts strong constraints on this event, as many scenarios lead to the loss of Hyperion (usually through collision with Titan). Here I report on the ongoing study of the history of the Saturnian system, using symplectic integrators SIMPL (for stable configurations) and COMPLEX (for situations when the moons' orbits crossed). I find that the past system of icy satellites could have naturally evolved into instability, by having Dione and Rhea-like moons enter the mutual 4:3 resonance. This resonance is chaotic due to overlap with the solar evection resonance (i.e. the moons' precession rates in the mean-motion resonance overlap with Saturn's mean motion). The outcome of such resonance is a collision between the mid-sized moons, likely followed by re-accretion, with Titan being largely unaffected. I also find that close encounters between a mid-sized moon and Titan could with significant probability both excite Titan and preserve its resonance with Hyperion (cf. Hamilton 2013). I will present possible scenarios in which the previous system had an additional moon exterior to Rhea. This additional moon would have been destabilized by resonances with the inner moons and eventually absorbed by Titan, which acquired its eccentricity in the process. This research is supported by NASA's Outer Planet Research Program.

Author(s): ***Matija Cuk (SETI Institute)***

301.02 The Origin of Titan and Hyperion

Titan is arguably the Solar System's most unusual satellite. It is fifty times more massive than Saturn's other moons and is the only satellite with a substantial atmosphere. Titan shares a unique resonance with nearby Hyperion, but otherwise sits in a particularly large gap between Rhea and Iapetus. Titan has the largest eccentricity of all Saturn's regular satellites and has a reasonably large orbital tilt; its distant neighbor Iapetus has an even more impressive eight degree free inclination. Hyperion itself is a mystery, with its unusual orbit, extremely low density and its unique surface covered with bizarre craters. None of these peculiarities are even partially understood. Until now!

Author(s): ***Douglas Hamilton (Univ. of Maryland)***

301.03 On the time-variable nature of Titan's obliquity

Titan presents an unexpectedly high obliquity (Stiles et al. 2008, Meriggiola & Iess 2012) while its topography and gravity suggest a non-hydrostatic ice shell (Hemingway et al. 2013). We here present a 6-dof model of the rotation of Titan simultaneously simulating the full orientation of the shell and the inner core, and considering a global subsurface ocean with a partially-compensated shell of spatially-variable thickness. Between 10 and 13% of our realistic interior models induce a resonance with the annual forcing, that dramatically raises the obliquity. The relevant model Titans are composed of a 130-140 km thick shell floating on a ~250 km thick ocean. The observed obliquity should not be considered as a mean one but as an instantaneous one, that should vary by ~7 arcmin over the duration of the Cassini mission.

Author(s): ***Benoit Noyelles (University of Namur)***, Francis Nimmo (University of California)

301.04 Dynamical Fate of Clumps Formed in Satellite Mergers.

The middle-sized moons (MSMs) of Saturn are icy bodies approximately 300-1500 km diameter, whose cumulative mass is approximately 5% the mass of Titan. Although it is generally thought that they accreted from a gas and particle disk around Saturn [Charnoz, S. et al. (2011), Canup, R. M. & Ward, W. R. (2006)], this classical scenario seems unable to explain their diverse geology and composition, ranging from pure ice to mostly rock. Recently the idea that the MSMs (and perhaps Titan) formed in a series of collisions has flourished [Sekine & Genda, H. (2012), Asphaug, E. & Reufer, A. (2013), Hamilton, D. P. (2013) AAS/DPS Meetings, Cuk, M. (2013) ASU, SESE Colloquium]. Sekine & Genda (2012) proposed that the MSMs are remnants of a hit and run collision into a disappeared Titan-like satellite of Saturn. Asphaug & Reufer (2013) proposed instead that they are unaccreted remnants from the few collisional mergers that formed Titan. In each scenario, the main uncertainty and skepticism, which motivates the research presented here, is whether unaccreted or hit and run remnants can attain stable orbits and avoid becoming accreted. We study the dynamical fate of clumps formed in satellite mergers by coupling N-body simulations with the results of collisional mergers in SPH simulations. We define stable orbital configurations of one or more satellites in a planetary system in which a collision (merger or other giant impact) is assumed to have occurred. The outcome of different SPH simulations, representative of realistic collisions (mergers, hit and runs, disruptions), is integrated using the N-body integrator Mercury [Chambers, J. E. (1999)]. We study a variety of scenarios, including: single major collisions, multiple major collisions and successions of major collisions. External perturbations that would cause the system to go unstable in the first place and trigger the major collisions are also studied. We aim to identify the characteristic fraction of clumps from collisional mergers that would avoid accretion and attain long-term stable orbital evolutions along with the common characteristics that they share and the types of collisions and scenarios more propense to a higher survival rate.

Author(s): ***Desireé Cotto-Figueroa (Arizona State University)***, Erik Asphaug (Arizona State University), Andreas Reufer (Arizona State University)

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302 Understanding the Milky Way Globular Clusters, Sourav Chatterjee (University of Florida)

Wednesday, 11:20 AM - 12:00 PM; Mitchell Hall

302.01 Understanding the Milky Way Globular Clusters

Studying the evolution of globular clusters is of great interest for a variety of branches in astrophysics and cosmology. The high masses and stellar densities make them important targets for Galactic and extragalactic astronomy, and hotbeds for strong dynamical encounters facilitating several exotic sources. Their old ages provide a direct window into the major star formation episodes in the early universe. Until recently our numerical understanding for these systems was either limited by the number of stars simulations can treat or by omission of some physical processes. Northwestern group's Hénon-type Monte Carlo code CMC can lift these problems and allows creation of star-by-star cluster models that can be directly compared with the observational data. I will present our latest understanding of how these clusters evolve as a whole, explain bulk properties of the Milky Way globular clusters, and identify formation channels for some resolved exotic stellar populations.

Author(s): ***Sourav Chatterjee (University of Florida)***

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303 Modeling the Formation and Evolution of Dense Stellar System, Stephen McMillan (Drexel University)

Wednesday, 12:00 PM - 12:40 PM; Mitchell Hall

303.01 Modeling the Formation and Evolution of Dense Stellar Systems

Dense stellar systems -- star forming regions, young star clusters, globular clusters, and galactic nuclei -- are complex environments in which many physical processes compete to control the overall dynamics and long-term evolution. Of particular interest is the interplay between radiation, gas dynamics, stellar dynamics, and stellar and binary physics in determining the fates of these systems. However, modeling the combined effects of all these processes places stringent demands on both simulation software and computer hardware. As part of an ongoing effort to understand cluster formation and evolution, I will describe the Astrophysical MUltiphysics Software Environment (AMUSE), a general-purpose framework for combining multiple high-performance simulation modules within a homogeneous software interface. I will present some applications of AMUSE to simulations of various stages of cluster evolution, including hierarchical assembly, radiative feedback from massive stars and the ejection of residual gas, and the longer-term dynamics of the system.

Author(s): ***Stephen McMillan (Drexel Univ.)***

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304 The Solar System: Moons

Wednesday, 2:00 PM - 4:00 PM; Mitchell Hall

304.01 The Orbital and Interior Evolution of Charon as Preserved in its Geologic Record

Pluto and its largest satellite, Charon, currently orbit in a mutually synchronous state, which is a natural end-state for bodies that have undergone tidal dissipation. Charon's zero eccentricity and synchronous rotation means that it likely experiences very limited tidal deformation because the direction of, and distance to, Pluto remains the same throughout each orbit. In order to achieve this state, however, both bodies would have experienced tidal heating and stress. The extent of tidal activity is controlled by the orbital evolution of Pluto and Charon and by the interior structure and rheology of each body. As the secondary, Charon would have experienced a larger tidal response than Pluto, which may have manifested as observable tectonism. Unfortunately, there are few constraints on the interiors of Pluto and Charon. In addition, the pathway by which Charon came to occupy its present orbital state is uncertain. Recent efforts to model the orbital evolution of Pluto and its satellites indicate that Charon likely had a high eccentricity during its orbital expansion (e.g. Cheng et al., 2014). If Charon's orbit experienced a high-eccentricity phase in the past, tidal effects could have been more significant. We, thus, determine the conditions under which Charon could have experienced tidally-driven geologic activity and the extent to which upcoming New Horizons spacecraft observations could be used to constrain Charon's internal structure and orbital evolution. Using plausible interior structure models that include an ocean layer, we find that tidally-driven tensile fractures would likely have formed on Charon if its eccentricity were of order 0.01, especially if Charon were orbiting closer to Pluto than at present. Such fractures could display a variety of azimuths near the equator and near the poles, with the range of azimuths in a given region dependent on longitude. In contrast, east-west-trending fractures should dominate at mid-latitudes. The fracture patterns we predict indicate that Charon's geologic record could provide constraints on the thickness and viscosity of Charon's ice shell at the time of fracture formation.

Author(s): ***Alyssa Rhoden (NASA Goddard)***, Wade Henning (University of Maryland, College Park), Terry Hurford (NASA Goddard), Douglas Hamilton (University of Maryland, College Park)

304.02 Chaotic Rotation of Nix and Hydra

Disk-integrated photometry of Hydra and Nix from HST during 2010-2012 show large variations, which can be attributed to a combination of the phase function and the rotational light curves of the moons. After dividing out a model phase curve, variations by more than a factor of two remain, indicating that both Nix and Hydra are distinctly irregular in shape. Unexpectedly, Nix and Hydra's variations show no correlation with orbital longitude, as one would expect for bodies in synchronous rotation. In fact, Fourier analysis of the measurements does not reveal any fixed rotation periods compatible with the data. Compounding the mystery, Nix increased in absolute brightness by about 30% between 2010 and 2012, whereas Hydra was stable. I have developed a numeric integrator that tracks the position, velocity, orientation and rotation state of a moon as it orbits the Pluto-Charon "binary planet". The moons are represented by triaxial ellipsoids with arbitrary axial ratios. Pluto and Charon follow circular orbits about their common barycenter. I have run simulations for periods of up to 1000 years and for a variety of axial ratios and starting conditions. If an object is started in synchronous rotation with its long axis pointed toward the system barycenter, then it remains synchronously locked for the duration of the integrations. However, other initial conditions commonly lead to chaotic rotation, with Lyupanov times as brief as 30 days. Moons will sometimes temporarily lock into a nearly fixed rotation state, but commonly break out again within ~ 500 days. Depending on the axial ratios, polar flips are also commonly observed; this polar wander provides a plausible explanation for the year-by-year change in the observed brightness of Nix. Chaotic rotation is rare in the solar system, having previously been noted only for Hyperion and possibly Nereid. However, both photometry and dynamical simulations support the notion that chaotic rotation is a natural state for irregularly-shaped bodies orbiting a binary planet, with Nix and Hydra as real-world examples.

Author(s): ***Mark Showalter (SETI Institute)***

304.03 Seeding Life on the Moons of the Outer Planets

We performed N-body simulations which show that there could be material, and thus possibly life, from Earth or Mars on Europa and several other potentially habitable moons. Rock fragments from the surface of a planet can be ejected into space by a large impact. We simulated the trajectories of such ejecta to determine where in the Solar System rock from Earth and Mars may end up. It appears that transfer among the terrestrial planets is common, and transfer to the moons of Jupiter and Saturn is rare but possible.

Author(s): ***Rachel Worth (The Pennsylvania State University)***

304.04 Mimas' physical forced libration places strong constraints on its interior and origin.

Among the main moons, Mimas is the smallest and the closest to Saturn. It has a low surface temperature and no observed geological activity. By using Cassini ISS images, we built a network of 260 control points to measure Mimas' physical forced libration amplitude. Its value is twice the theoretically predicted one, which is based on the assumption of hydrostatic equilibrium. We present two models consistent with the measured libration amplitude: a subsurface ocean, and an elongated core. While the origin and sustenance of an ocean would be difficult to explain, the latter could be caused by the core being formed closer to Saturn. Due to its close distance to the primary, the core would adopt an elongated shape that has been unchanged until today due to its cold temperature. Such model would be in agreement with some recent satellite formation models of the rings (Charnoz et al. 2010, Charnoz et al. 2011, Crida & Charnoz 2012).

Author(s): ***Radwan Tajeddine (Cornell University, IMCCE/UPMC)***, Nicolas Rambaux (IMCCE/UPMC), Valery Lainey (IMCCE/UPMC), Sebastien Charnoz (CEA), Attilio Rivoldini (ROB), Andy Richard (IMCCE/UPMC), Benoit Noyelles (Namur University)

304.05 The Small Saturnian Satellites -- Chaos and Conundrum

From an analysis of Hubble Space Telescope data French et al. (2003 Icarus, 162, 143) found that the orbits of Prometheus and Pandora, which flank Saturn's F~ring, exhibited unexpected variations in their semimajor axes and mean motions. Goldreich and Rappaport (2003 Icarus, 162, 391) showed that those variations were caused by a chaotic interaction between the satellites. We report on the practical consequences that the chaos has on the production of ephemerides needed to support the Cassini mission and on the post Cassini ephemerides. Recently El Moutamid et al. (2014 Celest. Mech., 118, 235) proposed that the motions of three other satellites, Anthe, Methone, and Aegaeon could also be chaotic as a result of their mean motion resonances with Mimas. Coincidentally, the current orbits of the three satellites are a poor fit to the Cassini imaging data even though the direct perturbation of Mimas is included in the orbit computations. We discuss the status of our attempts to improve the orbit modelling for these satellites and the implications of their possibly chaotic behavior. Daphnis is a small satellite orbiting in the narrow (40 km) Keeler Gap in Saturn's rings. It was discovered in 2004 and found to have a near circular orbit in the ring gap. That orbit fits Cassini imaging data from 2004 to 2010 quite well, but it cannot fit the imaging acquired subsequent to late 2012. To fit the later data requires a circular orbit with a semimajor axis some 3 km larger. Moreover, no observations were made between 2010 and late 2012. We speculate on possible causes for the orbit change.

305 Poster Session

Wednesday, 5:00 PM - 7:00 PM; Mitchell Hall

305.01 Generating unaveraged equations of motion in common orbital elements

Cartesian equations of motion must be converted or integrated in order to impart information about the evolution of orbital elements such as the semimajor axis, eccentricity, inclination, longitude of ascending node, argument of pericentre and true anomaly. Alternatively, equations of motion in terms of only these orbital elements can reveal aspects of the motion simply by inspection. I advertise a quick method to generate such equations for perturbed two-body problems, where the perturbation may be arbitrarily large, and where no averaging is involved. I use the method to generate complete unaveraged equations from perturbations due to Poynting-Robertson drag, general relativity, mass loss, Galactic tides, and additional massive bodies under the guise of the general restricted few-body problem.

Author(s): ***Dimitri Veras (University of Warwick)***

305.02 URAT: year 3

The USNO Robotic Astrometric Telescope (URAT) is now in the third year of observing. Survey observing began in April 2012 at the Naval Observatory Flagstaff Station (NOFS). URAT has taken over 50,000 exposures of the northern sky with multiple overlaps, 28 sq. degrees with a single exposure at 0.9"/pixel resolution. Raw data processing, quality control, and scheduling are performed automatically. In normal survey mode URAT covers stars in the R = 10.5 to 18.0 magnitude range. Utilizing an objective grating and the clocked anti blooming feature of the 4 CCD chips results in a bright limit of 3rd magnitude. Exposures taken on the east and west side of the pier enable the calibration of potentially significant systematic errors. URAT mean positions are predicted to be on the 5 to 20 mas level depending on brightness and sky coverage. URAT will also provide proper motions and parallaxes for nearby stars, independent of any selection criteria. We are currently working on the reduction pipeline and a first astrometric catalog is expected to be released in 2014.

Author(s): ***Charlie Finch (US Naval Observatory)***, Norbert Zacharias (US Naval Observatory), Mike DiVittorio (US Naval Observatory), Eric Ferguson (US Naval Observatory), Hugh Harris (US Naval Observatory), Fred Harris (US Naval Observatory), Chris Kilian (US Naval Observatory), Ted Rafferty (US Naval Observatory (retired)), Albert Rhodes (US Naval Observatory), Michael Schultheis (US Naval Observatory), John Subasavage (US Naval Observatory), Trudy Tilleman (US Naval Observatory), Gary Wieder (US Naval Observatory)

305.03 Celestial Navigation in the 21st Century

Despite the ubiquity of GPS receivers in modern life for both timekeeping and geolocation, other forms of navigation remain important because of the weakness of the GPS signals (and those from similar sat-nav systems) and the ease with which they can be jammed. GPS jammers are available for sale on the Internet. The defense and civil aviation communities are particularly concerned about “GPS denial”, whether intentional or accidental, during critical operations. Automated star trackers for navigation have been available since the 1950s. Modern compact observing systems, operating in the far-red and near-IR bands, can detect useful numbers of stars even in the daytime at sea level. A capability to measure the directions of stars relative to some local set of coordinate axes is advantageous for many types of vehicles, whether on the ground, at sea, in the air, or in space, because it provides a direct connection to the inertial reference system represented by current star catalogs. Such a capability can yield precise absolute orientation information not available in any other way. Automated celestial observing systems can be effectively coupled to inertial navigation systems (INS), providing “truth” data for constraining the drift in the INS navigation solution, even if stellar observations are not continuously available due to weather. However, obtaining precise latitude and longitude from stellar observations alone, on a moving platform, remains a challenge, because it requires a determination of the direction to the center of the Earth, i.e., the gravity vertical. General relativity tells us that on-board (“lab”) measurements cannot separate the acceleration of gravity from the acceleration of the platform. Various schemes for overcoming this fundamental problem have been used in the past, at low accuracy, and better ones have been proposed for modern applications. This paper will review some recent developments in this rapidly advancing field.

Author(s): ***George Kaplan (George H. Kaplan, PhD)***

305.04 The Galilean moons orbital constraints and the improved orbit of Jupiter based on the radar ranging data

We investigate how the addition of the radar ranging measurements to the existing astrometry of the Galileans would improve their orbital parameters. We use simulated radar ranging measurements in combination with a handful of the existing ones (Harmon et al., 2007) in order to estimate the need for the future radar experiments at Arecibo and Goldstone. Radar ranging measurement are significantly more accurate than the most precise optical astrometry (~10-15 km vs 75 km) and could potentially help refine the tidal dissipation of Jupiter (parametrized by k2/Q, where k2 is the Love number and Q is the quality factor). The current estimate of the tidal dissipation has been obtained using optical astrometry only (Lainey et al. 2009). The results of our analysis show that a ground-radar observational campaign that spans several years would also benefit the development of the planetary ephemerides for Jupiter. In general, improved planetary and jovian satellite ephemerides would support future missions (e.g. Europa Clipper) and radar confirmation (or exclusion) of the orbital acceleration that is caused by tidal dissipation would complement the Juno mission’s gravity science experiment. Acknowledgments: The research described in this abstract was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

Author(s): ***Marina Brozovic (Jet Propulsion Laboratory/Caltech)***, Robert Jacobson (Jet Propulsion Laboratory/Caltech), William Folkner (Jet Propulsion Laboratory/Caltech)

305.05 Astrometry of natural satellites: improving the dynamics of planetary systems with old observations.

A new astrometric reduction of old photographic plates, benefiting from modern technologies such as sub-micrometric scanners associated with a reduction using accurate catalogues (UCAC at the present time and GAIA in a near future), provides improved knowledge of the orbital motion of planetary satellites. In the framework of an international collaboration first, and in the FP7 ESPaCE european project afterward, U.S. Naval Observatory plates were digitized with the new generation DAMIAN scanning machine of the Royal Observatory of Belgium. The procedure was applied to a few hundred photographic plates of the Galilean satellites covering the years 1967-1998, and of the Martian satellites covering the years 1967-1997. We provide results with an accuracy better than 70 mas in (RA,Dec) positions of the Galilean moons, and better than 60 mas in (RA,Dec) positions of the Martian satellites. Since the positions of Jupiter and Mars may be deduced from the observed (RA,Dec) positions of their satellites, we can also assess the accuracy of the

Thursday, 1 May 2014

400 The Solar System: Early Evolution

Thursday, 9:00 AM - 10:00 AM; Mitchell Hall

400.01 A few points on the dynamical evolution of the young solar system

The phenomenon of planetesimal-driven giant planet migration in the early history of our planetary system has become increasingly recognized as a key process for understanding the overall solar system architecture and its dynamical evolution. The dynamical structure of the Kuiper belt indicates that such migration caused Neptune's orbit to expand outward from its birth orbit by about 10 AU. It follows from energy and angular momentum conservation that a few tens of earth-masses of leftover planetesimals were ejected from the early solar system, and that Jupiter migrated inward by a few tenths of an AU. The orbital distribution of asteroids near resonances provides independent estimates of Jupiter's and Saturn's migration. An initially slow migration of the giant planets may have been accelerated during a brief but dramatic orbital instability due to planet-planet resonant encounters. While there is compelling evidence in the outer solar system for the above scenario, there is also tension with the observed properties of the inner solar system: the migration of the giant planets, with or without resonant encounters, would have caused severe, potentially destabilizing, perturbations on the inner planets' orbits. I will describe these considerations and some ideas for resolving this crisis in our understanding of the dynamical history of the solar system.

Author(s): ***Renu Malhotra (Univ. of Arizona)***

400.02 Planetary chaotic zone clearing: destinations and timescales

It is well known that there exists an annular zone in the vicinity of a planet's orbit where circular orbits are strongly chaotic due to the overlap of first order mean motion resonances. What is the final destination of these strongly chaotic orbits? What fraction impact the star, impact the planet or escape to infinity, and on what timescales? We explore these questions within the framework of the circular, planar restricted three body problem for planet-star mass ratios in the range 10^-9 to 10^-1.5. We find that most particles from the chaotic zone collide with the planet for low masses; particles can be scattered into unbound orbits only by higher mass planets. The chaotic zone clearing timescale is found to have a broken power-law dependence on the planet's mass, with a shallower power-law at low masses transitioning to a steeper power law at larger masses.

Author(s): ***Sarah Morrison (Univ. of Arizona)***, Renu Malhotra (Univ. of Arizona)

400.03 The Dynamics Of Inner Solar System Bodies With 2.8 < Tj < 3.2 And The Implications For The Origin Of Main-Belt Comets

Main-belt comets (MBCs) have attracted a great deal of interest since their identification as a new class of bodies by Hsieh and Jewitt in 2006. Much of this interest is due to the implication that MBC activity is driven by the sublimation of volatile material (presumed to be water ice) presenting these bodies as probable candidates for the delivery of a significant fraction of the Earth's water. An interesting characteristic of these objects is that while similar to comets, they have comae and dusty tails, they resemble asteroids, dynamically (i.e., their Tisserand numbers with respect to Jupiter, Tj, are larger than 3). The Tisserand parameter is a conserved quantity in the restricted three-body problem, and the Tisserand parameter with respect to Jupiter is frequently used to distinguish between asteroids (Tj>3), which are thought to be stable on Gyr timescales, and comets (Tj<3), which are thought to have dynamical lifetimes on the order of 10^5-10^6 yr before colliding with the Sun or being ejected from the solar system. Since the solar system is of course significantly more complex than the idealized three-body system assumed in the derivation of the Tisserand parameter, however, the boundary line between asteroids and comets is in fact not as distinct as the common use of the Tisserand parameter would suggest. We studied the dynamical evolution of test particles with Tisserand numbers ranging from 2.8 to 3.2 to explore the behavior of solar system objects (such as MBCs) with Tj values close to the canonical asteroid-comet boundary of 3. We find, as expected, that Tj is not a hard boundary between asteroids and comets, and that we can expect to find objects that are dynamically stable (over the time period of integrations) with Tj<3 as well as objects that are dynamically unstable with Tj>3. Dynamical stability can be seen to be a function of not just Tj, but also other orbital elements such as the eccentricity and aphelion distance. We will report on the detailed findings of our analysis and discuss their implications for the origin of MBCs.

Author(s): ***Nader Haghighipour (Institute for Astronomy, University of Hawaii)***, Henry Hsieh (Institute of Astronomy and Astrophysics, Sinica)

401 The Solar System: Debris

Thursday, 10:00 AM - 10:40 AM; Mitchell Hall

401.01 Transfer of Impact Ejecta Between Pluto and Charon

We have simulated the dynamical behavior of hypothetical ejecta from Pluto and Charon produced by the impact of bodies that traverse the Kuiper Belt. We integrated the orbits of impact ejecta with the SWIFT RMVS3 integrator. We performed sets of integrations of test particles from a range of longitudes on Pluto and Charon and included all the known bodies in the system (Pluto, Charon, Styx, Nix, Kerberos, and Hydra) in our calculations. The slowest ejecta land on the body from which they were launched, possibly making secondary craters. Ejecta at speeds slightly above the effective escape velocity from Pluto or Charon (1.18 and 0.55 km/s, respectively) go into short-lived orbits around Pluto/Charon and, in some cases, strike the other body. Higher-speed ejecta go into heliocentric orbit. We estimate that KBOs with diameters larger than 1 km strike Pluto and Charon on timescales of 0.4 and 1.7 million years at present, but these numbers are very uncertain. Assuming typical impact speeds of 2 km/s for KBOs onto Pluto and Charon, we estimate that about 10% of ejecta from Pluto strike Charon, while only 1% of ejecta from Charon strike Pluto. Measurement of the crater size-frequency distributions on Pluto and Charon by New Horizons will provide estimates of the small KBO population that may be unmatched by either ground- or space-based observations for some time.

Author(s): ***Henry Dones (Southwest Research Inst.)***, Edward Bierhaus (Lockheed Martin Space Systems Company)

401.02 A steady-state model of the lunar ejecta cloud

Every airless body in the solar system is surrounded by a cloud of ejecta produced by the impact of interplanetary meteoroids on its surface [1]. Such ``dust exospheres'' have been observed around the Galilean satellites of Jupiter [2,3]. The prospect of long-term robotic and human operations on the Moon by the US and other countries has rekindled interest on the subject [4]. This interest has culminated with the - currently ongoing - investigation of the Moon's dust exosphere by the LADEE spacecraft [5]. Here a model is presented of a ballistic, collisionless, steady state population of ejecta launched vertically at randomly distributed times and velocities and moving under constant gravity. Assuming a uniform distribution of launch times I derive closed form solutions for the probability density functions (pdfs) of the height distribution of particles and the distribution of their speeds in a rest frame both at the surface and at altitude. The treatment is then extended to particle motion with respect to a moving platform such as an orbiting spacecraft. These expressions are compared with numerical simulations under lunar surface gravity where the underlying ejection speed distribution is (a) uniform (b) a power law. I discuss the predictions of the model, its limitations, and how it can be validated against near-surface and orbital measurements. [1] Gault, D. Shoemaker, E.M., Moore, H.J., 1963, NASA TN-D 1767. [2] Kruger, H., Krivov, A.V., Hamilton, D. P., Grun, E., 1999, Nature, 399, 558. [3] Kruger, H., Krivov, A.V., Sremcevic, M., Grun, E., 2003, Icarus, 164, 170. [4] Grun, E., Horanyi, M., Sternovsky, Z., 2011, Planetary and Space Science, 59, 1672. [5] Elphic, R.C., Hine, B., Delory, G.T., Salute, J.S., Noble, S., Colaprete, A., Horanyi, M., Mahaffy, P., and the LADEE Science Team, 2014, LPSC XLV, LPI Contr. 1777, 2677.

Author(s): ***Apostolos Christou (Armagh Obs.)***

402 The Solar System: Rings

Thursday, 11:00 AM - 1:00 PM; Mitchell Hall

402.01 Architecture of the Cassini Division revisited

In their study of gaps and ringlets in the Cassini Division of Saturn's rings, Hedman & Nicholson (2010) found that the inner edges of all eight gaps were noncircular, with all but two being well-modeled as precessing keplerian ellipses. The apsidal precession rates seemed to form a regular arithmetic sequence, with an interval of ~0.06 deg/day, which they attributed to a possible 3-body resonance with Mimas and the nearby outer edge of the B ring. We have now extended this study to include not only more recent stellar occultation measurements by the Cassini-VIMS instrument and Cassini radio occultations, but also similar data from the Cassini UVIS instrument. With a data set roughly 4 times larger, and now extending over more than 5 years, we have re-examined the shapes of all 16 gap edges in this region, as well as those of the four associated narrow ringlets. We confirm that five of the eight gaps have essentially circular outer edges, with the exception of the Huygens, Herschel and Laplace gaps whose edges show variations at the 1-2 km level. In accord with Hedman & Nicholson (2010), we find that six of the eight gaps have elliptical inner edges, with amplitudes ranging from 0.9 to 8.4 km and precession rates which are close to, but slightly larger than, those calculated from Saturn's zonal gravity coefficients. Although more recent studies of the B ring edge by Spitale & Porco (2010) and Nicholson etal (2014) cast doubt on the 3-body resonance model, the regular spacing of the eccentric gap edges remains a striking feature. We will present a new study of their pericenter distribution, with the goal of elucidating any underlying resonant structure and the process which has created the gaps.

Author(s): ***Philip Nicholson (Cornell University)***, Richard French (Wellesley College), Matthew Hedman (University of Idaho), Joshua Colwell (University of Central Florida), Essam Marouf (San Jose State University), Colleen McGhee (Wellesley College)

402.02 Dynamical models of Saturn's Phoebe ring

Saturn has the distinction of hosting the largest observed ring system in the solar sytem, the Phoebe Ring. Its vertical extent implicates Saturn’s irregular and distant satellite Phoebe as the source, with material being liberated through collisions. Owing to radiation forces, dusty debris is then swept inward toward Saturn on long timescales, spreading into a disk two orders of magnitude larger than Saturn’s more famous main rings. Previous work indicates that Saturn’s moon Iapetus should sweep up the majority of this infalling dark material. This would explain its striking two-faced surface, with one hemisphere ten times darker than the other. However, there is yet no direct observational confirmation of this mass transfer process. An important prediction for this model of Iapetus’ hemispherical dichotomy is that Iapetus should carve out an inner edge to the Phoebe ring. While scattered light from Saturn thwarts all attempts to detect this inner edge from Earth, we have recently developed a technique for detecting the Phoebe ring using the Cassini spacecraft. Preliminary work suggests we have found such an inner edge. In order to meaningfully interpret our findings, we require a dynamical model for the debris decaying inward from Phoebe. We will present the results of our analytical and numerical investigations.

Author(s): ***Daniel Tamayo (Cornell University)***, Stephen Markham (Cornell University), Matthew Hedman (University of Idaho), Joseph Burns (Cornell University)

402.03 An unusual density wave in Saturn's C ring, evidence for a supersonic resonance?

Resonances with periodic perturbing forces in dense ring systems generate distinctive spiral patterns known as density waves. In Saturn's rings, density waves are most often found at Lindblad resonances with Saturn's various moons, but several waves in the C ring are not found near any known resonance with any known moon. By comparing multiple occultation profiles of these waves, we were able to determine the pattern speeds and number of arms in these spiral patterns, and thereby demonstrate several of these waves are likely due to normal mode oscillations inside the planet (Hedman and Nicholson, AJ 2013). Applying these same methods to yet another wave situated between 85,670 and 86,700 km from Saturn's center, we obtained some very surprising results. This feature appears to be most consistent with a one-armed spiral pattern rotating around the planet at nearly twice the local mean motion, which would suggest that this structure is generated by an 1:2 Outer Lindblad Resonance. However, the radial wavelength of the spiral pattern decreases with increasing radius, which is a characteristic of waves generated by Inner Lindblad Resonances (whose pattern speeds are slower than the local mean motion). This inconsistency could be the result of another highly unusual feature of this wave. Based on comparisons of Voyager and Cassini occultations, the wave appears to have been moving slowly inwards over the last 30 years, indicating that the frequency of the perturbing force responsible for generating this wave has been slowly changing. In fact, the drift rate of the resonant location appears to be larger than the group velocity of the wave, so that the resonance outruns the inward-propagating wave, effectively turning the entire pattern inside out.

Author(s): ***Matthew Hedman (University of Idaho)***, Philip Nicholson (Cornell University)

402.04 Collisional Features in Saturn's F Ring

Saturn’s F ring is a highly dynamic environment; changeable over timescales from hours to years and displaying a variety of features caused by both gravitational and collisional interactions with local objects. These objects range from the ‘shepherding’ moons Prometheus and Pandora down to small (radius <~1 km) moonlets, embedded in the ring or on nearby orbits. Previously (Attree et al. 2014) we catalogued nearly 900 small-scale collisional features (“mini-jets”) from Cassini images, placing constraints on the size and orbital distribution of the local colliding population. Here we will present the latest work on F ring collisions; updating the catalogue with new Cassini images to further refine our statistics of the population as well as discussing specific, interesting features which shed light on the collision process. We will also present the results of N-body simulations of the collisions and discuss ongoing work to survey the larger “jet” features. These are caused by higher velocity collisions (~30m/s) with more distant objects like S/2004 S 6 which may represent the upper end of the moonlet population in size and in orbit.

Author(s): ***Nicholas Attree (Queen Mary University of London)***, Carl Murray (Queen Mary University of London), Nicholas Cooper (Queen Mary University of London), Gareth Williams (Queen Mary University of London)

402.05 How can we explain the presence of rings around the Centaur Chariklo?

Recently two rings have been detected around the small body known as (10199) Chariklo (Braga-Ribas et al. 2014). Chariklo is the largest Centaur, with a diameter of 250 km and a dynamical lifetime estimated at less than 10 Myrs, given its orbital position. By the technique of multi-chord stellar occultation, Felipe Braga-Ribas and colleagues observed two dense rings around this asteroid separated by a gap of 14 km, with widths of 7 km and 3 km, optical depths 0.4 and 0.06, and radii from the central body of 391 km and 405 km, respectively. This raises several questions concerning the stability of such a ring system and its origin. In this talk we will try to present the first attempt at answering these issues from a dynamical point of view. The presence of rings around such a body is an exciting but surprising result. Several scenarios could account for their formation: - A violent impact such as the Moon-forming collision could potentially lead to the creation of a ring. - The potential presence of larger bodies surviving the initial impact and acting as shepherd satellites for the rings could make it long-lived. - Another scenario involves a small satellite (less than 2 km) which is destroyed by tidal effects as it migrates inwards to the Roche

Authors Index