2015 Meeting of the Division on Dynamical Astronomy

Pasadena, CA – May, 2015

Meeting Abstracts

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Sessions With Abstracts

Welcome Address, Fred Adams (DDA Chair)

100 – Exoplanet Theory I

100.02 – Loners, Groupies, and Long-term Eccentricity (and Inclination) Behavior: Insights from Secular Theory

Considering the secular dynamics of multi-planet systems provides substantial insight into the interactions between planets in those systems. Secular interactions are those that don't involve knowing where a planet is along its orbit, and they dominate when planets are not involved in mean motion resonances. These interactions exchange angular momentum among the planets, evolving their eccentricities and inclinations. To second order in the planets' eccentricities and inclinations, the eccentricity and inclination perturbations are decoupled. Given the right variable choice, the relevant differential equations are linear and thus the eccentricity and inclination behaviors can be described as a sum of eigenmodes. Since the underlying structure of the secular eigenmodes can be calculated using only the planets' masses and semi-major axes, one can elucidate the eccentricity and inclination behavior of planets in exoplanet systems even without knowing the planets' current eccentricities and inclinations. I have calculated both the eccentricity and inclination secular eigenmodes for the population of known multi-planet systems whose planets have well determined masses and periods. Using this catalog of secular character, I will discuss the prevalence of dynamically grouped planets ('groupies') versus dynamically uncoupled planets ('loners') and how this relates to the exoplanets' long-term eccentricity and inclination behavior. I will also touch on the distribution of the secular eigenfreqiencies.

Author(s): Christa L. Van Laerhoven[1]
Institution(s): *1. University of Toronto, CITA*

100.03 – Obliquity Evolution of Earth-Like Exoplanets in Systems with Large Inclinations

In order to properly assess the potential for habitability and prioritize target selection for the characterization of exoplanets, we need to understand the limits of orbital and rotational dynamics. Large satellites may be rare and very difficult to detect. Consequently, it is necessary to quantify the likelihood of a planet’s having extreme obliquity cycles in the absence of a moon and to model the potential impact on the planet’s climate. We explore the obliquity evolution of (1) known exoplanet systems that could contain Earth-like planets in the habitable zone and (2) hypothetical planets in mutually inclined, chaotic resonant configurations that experience some of the most extreme orbital evolution possible. We use a secular obliquity model coupled to either an N-body models or a 4^{th} order secular orbital model.
We find that in some known systems, planets’ obliquity variations are small and unlikely to have a major effect on climate, unless undetected planets are present. Systems with three or more planets are significantly more dynamically rich, with planets that undergo obliquity changes of ~10° over 50,000 years and >30° over a few million years. In resonant configurations, Earth-like exoplanets can undergo dramatic and chaotic evolution in eccentricity and inclination while remaining stable for over 10 Gyr. In configurations in which eccentricities and inclinations stay below ~0.1 and ~10°, respectively, obliquities oscillate quasi-periodically with amplitudes similar to the non-resonant, three-planet configurations. In more dynamically active configurations, in which eccentricities and inclinations evolve to $e > 0.3$ and $i > 15°$, obliquities can extend from ~0° to well past 90°. In extreme cases eccentricities can reach >0.9999 and inclinations >179.9 degrees, driving precession rates in excess of degrees per year. However, these planets can graze or impact the stellar surface and are probably not habitable.

Author(s): Russell Deitrick[3], Rory Barnes[3], Richard Greenberg[2], Thomas R. Quinn[3], Sean N. Raymond[1]
Institution(s): *1. Laboratoire d'Astrophysique de Bordeaux, 2. University of Arizona, 3. University of Washington*

101 – Exoplanet Theory II

101.01 – Capture into Mean-Motion Resonances for Exoplanetary Systems

Many bodies in the Solar System and some exo-planets are close to or captured in Mean Motion Resonances (MMR). Capture into such resonances has been investigated by many authors. Indeed, the Hamiltonian equations of motion in presence of migration are given by Sicardy and Dubois Cel. Mech. & Dyn. Astron. , 86, 321-350 (2003). Fleming and Hamilton, Icarus 148, 479-493 (2000), studied the problem in a less generic context.
In these two papers, the authors studied the problem of 1:1 corotation (Lagrange points L4 and L5), rather than m+1:m corotations (El Moutamid et al, Cel. Mech. & Dyn. Astron, 118, 235-252 (2014)).
We will present a generic way to analyze details of a successful (or not) capture in the case of an oblate (or not) central

body in the context of Restricted Three Body Problem (RTBP) and a more General Three Body Problem in the context of known statistics for captured exoplanets (candidates) observed by Kepler.

Author(s): Maryame El Moutamid[1], Bruno Sicardy[3], Stéfan Renner[2]
Institution(s): *1. Cornell University, 2. Université Lille 1, IMCCE - Observatoire de Paris, 3. UPMC Paris 6, LESIA - Observatoire de Paris*

101.02 – Consolidating and Crushing Exoplanet Systems

Kepler revealed the common existence of tightly-packed planetary systems around solar-type stars, existing entirely on orbits with periods shorter than ~200 days. Those systems must have survived for the ages of their host stars (~5 Gyr), so their formation mechanism must provide inter-planet spacings that permit long-term stability. If one postulates that most planetary systems form with tightly-packed inner planets, their current absence in some systems could be explained by the collisional destruction of the inner system after a period of meta-stability. The signatures of such intense collisional environments may have been observed around stars in the form of rapidly varying debris disks; in these observed disks, collisional products are being disposed of via drag down onto the star or grinding to the nearly instantaneous dust blow-out limit. We use the orbital spacings and planet masses of the observed Kepler multi-planet systems to investigate the stability and long-term behavior of the systems. We find that many of our Kepler system analogs are unstable on 100 Myr timescales, even for initially small eccentricities (0-0.05); the instability timescales in these systems are distributed such that equal fractions of the systems experience planetary collisions in each decade in time. We discuss the likely outcomes of collisions in these systems based on the typical collision speeds from our numerical integrations and what implications this has for interpreting the observed Kepler multi-planet systems. The possible implications for our Solar System are discussed in a companion abstract (Gladman and Volk).

Author(s): Kathryn Volk[1], Brett Gladman[1]
Institution(s): *1. University of British Columbia*

101.03 – Mean Motion Resonances and the Origins of Extrasolar Orbital Architectures

The early stages of dynamical evolution of planetary systems are often shaped by dissipative processes that drive orbital migration. In multi-planet systems, convergent amassing of orbits inevitably leads to encounters with rational period ratios, which may result in establishment of mean motion resonances. The success or failure of resonant capture yields exceedingly different subsequent evolutions, and thus plays a central role in determining the ensuing orbital architecture of planetary systems. In this talk, we will show how an integrable Hamiltonian formalism for planetary resonances that allows both secondary bodies to have finite masses and eccentricities, can be used to construct a comprehensive theory for resonant capture. Employing the developed analytical model, we shall examine the origins of the dominantly non-resonant orbital distribution of sub-Jovian extrasolar planets, and demonstrate that the commonly observed extrasolar orbital structure can be understood if planet pairs encounter mean motion commensurabilities on slightly eccentric ($e \sim 0.02$) orbits. Accordingly, we speculate that resonant capture among low-mass planets is typically rendered unsuccessful due to subtle axial asymmetries inherent to the global structure of protoplanetary disks.

Author(s): Konstantin Batygin[1], Alessandro Morbidelli[2]
Institution(s): *1. California Institute of Technology, 2. Observatoire de la Cote d'Azur*

101.04 – Secular star-disk coupling and the origin of exoplanetary spin-orbit misalignments

A recent paradigm shift in exoplanetary astronomy has come with the detection of a substantial number of planets possessing orbits that are misaligned with respect to the spin axes of their host stars. Moreover, observations of misalignments now include coplanar, multi-transiting systems, suggesting that these planets inherited their orbital planes from a protoplanetary disk which was once itself inclined with respect to the star. It has been proposed that mutual star-disk inclination may arise as a consequence of turbulence within the collapsing molecular cloud core, out of which both the star and its disk form. Alternatively, misalignments may be attained later on, through secular interactions between the disk and companion stars. In this work, we examine the secular dynamics of the stellar spin axis arising in response to the gravitational and accretional torques communicated between the star and its disk throughout the epoch of star and planet formation. Our analysis shows that even though the disk forms from turbulent material, and is thus expected to exhibit a stochastic variation in its orientation with time during the star formation process, gravitational disk-star coupling adiabatically suppresses the excitation of mutual star-disk inclination under all reasonable parameter regimes. As such, the excitation of mutual star-protoplanetary disk inclination must occur later on in the disk's lifetime, by way of an encounter with a secular resonance between stellar precession and the gravitational perturbations arising from an external potential, such as a binary companion.

Author(s): Christopher Spalding[1], Konstantin Batygin[1], Fred C. Adams[2]
Institution(s): *1. California Institute of Technology, 2. University of Michigan*

101.05 – Inclination Excitation in Compact Extrasolar Planetary Systems

The Kepler Mission has detected dozens of compact planetary systems with more than four transiting planets. This sample provides a collection of close-packed planetary systems with relatively little spread in the inclination angles of the inferred orbits. We have explored the effectiveness of dynamical mechanisms in exciting orbital inclination in this class of solar systems. The two mechanisms we discuss are self-excitation of orbital inclination in initially (nearly) coplanar planetary systems and perturbations by additional unseen larger bodies in the outer regions of the solar systems. For both of these scenarios, we determine the regimes of parameter space for which orbital inclination can be effectively excited. For compact planetary systems with the observed architectures, we find that the orbital inclination angles are not spread out appreciably through self-excitation, resulting in a negligible scatter in impact parameter and a subsequently stable transiting system. In contrast, companions in the outer solar system can be effective in driving variations of the inclination angles of the inner planetary orbits, leading to significant scatter in impact parameter and resultantly non-transiting systems. We present the results of our study, the regimes in which each excitation method - self-excitation of inclination and excitation by a perturbing secondary - are relevant, and the magnitude of the effects.

Author(s): Juliette Becker[1], Fred C. Adams[1]
Institution(s): *1. University of Michigan*

102 – Planet Formation I

102.01 – Brouwer Award Lecture: Planetary Dynamics

Radial velocity and transit surveys indicate the presence of super Earth around half of the main sequence stars regardless of their mass and metallicity. In contrast, the frequency of gas giants is much lower and increases with stellar mass and metallicity. I will show how the emergence of super-Earth is a robust process whereas the formation of gas giant planets is a threshold phenomena. The topics to be discussed include physical barriers in the planet building process, the role of migration in their evolving natal disks, planets' interaction with each other and with their host stars. I will also discuss some key observations which may provide quantitative tests for planet formation theories.

Author(s): Douglas N. C. Lin[1]
Institution(s): *1. UC, Santa Cruz*

102.02 – Did our Solar System once have a STIP?

Continuing the established tradition in the field of speculative "fairy tales", we postulate that our Solar System once had a set of several additional Earth-scale planets interior to the orbit of Venus. This would resolve a known issue that the energy and angular momentum of our inner-planet system is best explained by accreting the current terrestrial planets from a disk limited to 0.7-1.1 AU; in our picture the disk material closer to the Sun also formed planets, but they have since been destroyed. By studying the orbital stability of systems like
the known Kepler systems, Volk and Gladman (companion abstract) demonstrate that orbital excitation and collisional destruction could be confined to just the inner parts of the system. In this scenario, our Mercury is the final remnant of the inner system's destruction via a violent multi-collision (and/or hit-and-run disruption) process.This would provide a natural explanation for Mercury's unusually high eccentricity and orbital inclination; it also fits into the general picture of long-timescale secular orbital instability, with Mercury's current orbit being unstable on 5 Gyr time scales. The common decade spacing of instability time scales raises the intriguing possibility that this destruction occurred roughly 0.6 Gyr after the formation of our Solar System and that the lunar cataclysm is a preserved record of this apocalyptic event that began when slow secular chaos generated orbital instability in our former super-Earth system.

Author(s): Brett Gladman[1]
Institution(s): *1. Univ. of British Columbia*

102.03 – The Formation of Terrestrial Planets from the Direct Accretion of Pebbles

Building the terrestrial planets has been a challenge for planetformation models. In particular, classical theories have been unable to reproduce the small mass of Mars and instead predict that a planet near 1.5 AU should roughly be the same mass as the Earth (Chambers 2001, icarus 152,205). Recently, a new model, known as *'slow pebble accretion'*, has been developed that can explain the formation of the gas giants (Levison+ 2015, Nature submitted). This model envisions that the cores of the giant planets formed from 100 to 1000 km bodies that directly accreted a population of pebbles (Lambrechts & Johansen 2012, A&A 544, A32) - centimeter- to meter-sized objects that slowly grew in the protoplanetary disk. Here we apply this model to the terrestrial planet region and find that it can reproduce the basic structure of the inner Solar System, including a small Mars and a low-mass asteroid belt. In particular, our models show that for an initial population of planetesimals with sizes similar to those of the main belt asteroids, slow pebble accretion becomes inefficient beyond ~1.5 AU. As a result, Mars's growth is stunted and nothing large in the asteroid belt can accumulate.

Author(s): Harold F. Levison[1], Katherine A. Kretke[1], Kevin J. Walsh[1]
Institution(s): *1. Southwest Research Inst.*

103 – Planet Formation II

103.01 – Tidal Effects in Late Stage Accretion

We model the effects of tidal dissipation in the late stages of planetary accretion. We investigate the tidal dissipation during close encounters between embryos and nearly-formed planets using a modified version of the N-body integrator SyMBA. We calculate a total energy lost due to tides per close encounter and estimate the change in velocities of the bodies at each encounter. We measure the effects on the dynamics, evolution, and final outcome of the planets. Our initial results show a clear separation between the tidal and non-tidal case for a relatively strong tidal dissipation factor. We compare these results to traditional late stage simulations both with and without fragmentation.

Author(s): Kevin Graves[1]
Institution(s): *1. Purdue University*

103.02 – The Öpik Approximation and Giant Planet Shielding of the Inner Solar System

Öpik (1976) proposed that close-range gravitational interactions between planetesimal material and planets could be approximated by a two-step integration scheme: (1) while the planetesimal was outside the gravitational sphere of influence of the planet, its orbit would be described by a heliocentric Keplerian orbit; and (2) once its orbit entered the sphere of influence of the planet, its trajectory would then become a planetocentric Keplerian orbit until it exited the sphere of influence and resumed a heliocentric path. This approximation, however, was also limited by the requirement noted by Öpik that the perihelion or aphelion distance of the planetesimal differ from the orbital distance of the planet from the sun. This approximation proved to be a useful tool during early solar system dynamical investigations but this process was often employed as a numerical integration method without checking Öpik's requirements, as well as establishing whether the orbital passage through the sphere of influence was sufficiently accurate. Öpik's scheme was used to establish many features of solar system evolution, including the commonly-held belief that the giant planets serve as a shield preventing substantial numbers of planetesimals from entering the inner solar system. Wetherill (1994) in a pioneering work that exploited the Öpik approximation as an integration scheme estimated that present-day Jupiter could prevent 99.9% of planetesimals from entering the inner solar system. Here, we employ high precision first-principles calculations of the orbits of swarms of planetesimals emerging from the Jupiter-Saturn, Saturn-Uranus, and Uranus- Neptune zones and have shown (1) the conditions necessary for Öpik's approximation to be valid fail for a substantial fraction of the planetesimal population during their lifetimes, and (2) approximately 44% of the planetesimal swarm originating in the Jupiter-Saturn zone alone are injected into the inner Solar System while 18% ultimately become Earth-crossers.

Author(s): William I. Newman[2], Philip W. Sharp[3], Kevin R. Grazier[1]
Institution(s): *1. Jet Propulsion Laboratory, 2. UC, Los Angeles, 3. University of Auckland*

103.03 – Implications of Resonant and Near-Resonant Planetary Systems for Planet Formation

Observations of strongly interacting planetary systems in or near a mean motion resonance are unusually sensitive to planet masses and orbital properties, including dynamical properties that can help illuminate planet formation. Having developed a powerful toolbox for translating Doppler and/or transit timing observations into physics parameters, now we are able to characterize the resonant and secular behaviour of several strongly interacting planetary systems. I will present recent results for selected resonant and near-resonant planetary systems and discuss implications for planet formation. In particular, I will address implications for the nature and extent of orbital migration for giant and low-mass planets.

Author(s): Eric B. Ford[1]
Institution(s): *1. Penn State*

103.04 – The fate of debris from a giant impact on Mars

We use published models for the formation of the ~$1x10^4$ km Borealis Basin on Mars from a ~2000 km impactor to investigate the fate of ejected debris. We use an n-body integrator to show that debris from this event could have been an important contributor to the cratering history of the Earth, Moon, and Mars well after the basin formed. We investigate whether this event could have been responsible for the Late Heavy Bombardment (LHB) on these planets. We show that the giant impact debris model has a number of features that are more favorable for explaining the LHB compared with giant planet instability models, such as the Nice model.

Author(s): David A. Minton[3], Alan Jackson[1], Erik Asphaug[1], Caleb I Fassett[2]

Institution(s): *1. Arizona State University, 2. Mount Holyoke College, 3. Purdue University*

200 – Ring Dynamics

200.01 – Irregular Structure in Saturn's Huygens Ringlet

Saturn's Huygens ringlet is a narrow eccentric ringlet located ~250 km exterior to the outer edge of Saturn's B ring. Based on about 5 years of Cassini observations, the ringlet contains multiple wavenumber-2 patterns superimposed on its edges (Spitale et al., in prep). Additional higher-order modes may be present, but a few km of radial variation on the edge of the ringlet likely cannot be explained by normal modes with pattern speeds appropriate for those modes. Instead, there is an irregular component to the ringlet's shape that moves at a speed near the local Keplerian rate and is recognizeable for multiple years. The pattern sometimes appears inverted, suggesting that the shape arises from a perturbation in eccentricity rather than semimajor axis. The synodic period between the inner and outer edges of the ring is ~5 years, so a significant evolution of the pattern would be expected if the shape were driven by multiple embedded perturbers distributed across the ring. The relatively static shape of the pattern may indicate that only perturbers with semimajor axes in a narrow region close to the edges of the ringlet play a role. A better understanding of the effect of embedded bodies on ring edges is needed.

Author(s): Joseph N. Spitale[1]
Institution(s): *1. Planetary Science Institute*

200.02 – The Titan -1:0 bending wave in Saturn's C ring

In 1988 Rosen & Lissauer identified an unusual wavelike feature in Saturn's inner C ring as a bending wave driven by a nodal resonance with Titan (Science 241, 690) This is sometimes referred to as the -1:0 resonance since it occurs where the local nodal regression rate is approximately equal to -n_T, where n_T = 22.577 deg/day is Titan's orbital mean motion. We have used a series of 44 stellar occultation profiles of this wave observed by the Cassini VIMS instrument to test their hypothesis. We find that, as predicted, this wave is an outward-propagating m=1 spiral with a leading orientation and a retrograde pattern speed equal to -n_T. Applying the standard linear dispersion relation (Shu 1984), we find a mean background surface mass density of 0.7 g/cm^2, similar to previous estimates for the inner C ring.

But the most intriguing feature of the wave is a narrow, incomplete gap which lies ~7 km outside the resonance. This gap varies noticeably in width and is seen in roughly 3/4 of the occultation profiles, appearing to rotate with the wave in a retrograde direction. We have developed a simple, kinematical model which accounts for the observations and consists of a continuous but very narrow gap (radial width = 0.5 km), the edges of which are vertically distorted by the propagating bending wave as it crosses the region. Differences in viewing geometry then largely account for the apparent width variations. We find a vertical amplitude of 3.8 km for the inner edge and 1.2 km for the outer edge, with nodes misaligned by ~110 deg. Moreover, both edges of the gap are slightly eccentric, with pericenters aligned with Titan, suggesting that the eccentricities are forced by the nearby Titan apsidal resonance. We hypothesize that the gap forms because the local slope of the ring becomes so great that nonlinear effects result in the physical disruption of the ring within the first wavelength of the bending wave. However, the vertical relief on the gap edges is ~10 times the predicted amplitude of the bending wave, so this story may be incomplete.

Author(s): Philip D. Nicholson[1], Matthew M. Hedman[2]
Institution(s): *1. Cornell Univ., 2. University of Idaho*

200.03 – Saturn Ring Seismology: How ring dynamics reveal the internal structure of the planet

Seismology allows for direct observational constraints on the interior structures of stars and planets. Recent observations of Saturn's ring system have revealed the presence of density waves within the rings excited by oscillation modes within Saturn, allowing for precise measurements of a limited set of the planet's mode frequencies. Additional ring waves are created at Lindblad resonances with density inhomogeneities in the planet, allowing for measurements of internal differential rotation. I construct interior structure models of Saturn, compute the corresponding mode frequencies, and compare them with the observed mode frequencies. The observed modes, some of which are finely split in frequency, can only be reproduced in models containing gravity modes that propagate in a stably stratified region of the planet. The stable stratification must exist deep within the planet near the large density gradients between the core and envelope. The planetary oscillation modes may in turn influence the evolution of the rings by depositing angular momentum at Lindblad resonances. In particular, the Maxwell gap is likely opened due to a resonance with Saturn's l=m=2 fundamental mode.

Author(s): Jim Fuller[1]
Institution(s): *1. California Institute of Technology*

200.04 – Saturn's F ring: A decade of perturbations and collisions

We present an overview of the gravitational and collisional processes at work in Saturn's F ring deduced from images obtained by the Imaging Science Subsystem (ISS) on the Cassini spacecraft since 2004. The moon Prometheus exerts the dominant gravitational perturbation on the ring. As well as creating the observed periodic "streamer-channel" structures in the ring, there is evidence that Prometheus also causes the formation and orbital evolution of clumps that can, in turn, perturb local ring particles. We show how Prometheus' effect can be understood in terms of a simple epicyclic model. Jets of material seen emanating from the F ring are produced when objects orbiting nearby collide with material in the core. We show that there are fundamental differences between the larger and smaller jets even though both are caused by collisions. A comparison between the morphology seen in ISS observations and the results of simulations suggests that both the impactors and the core material are in the form of aggregates of material. We present the results of a study of one particular sheared jet and its associated clumps over a two-month interval in early 2008, deriving orbits for the clumps and showing how they change as they encounter Prometheus.

Author(s): Carl D Murray[1], Nicholas Cooper[1], Nicholas Attree[1], Gareth Williams[1]
Institution(s): *1. Queen Mary University of London*

200.05 – How massive is Saturn's B ring? Clues from cryptic density waves

The B ring is the brightest and most opaque of Saturn's rings, but it is also amongst the least well understood because basic parameters like its surface mass density are still poorly constrained. Elsewhere in the rings, spiral density waves driven by resonances with Saturn's various moons provide precise and robust mass density estimates, but for most the B ring extremely high opacities and strong stochastic optical depth variations obscure the signal from these wave patterns. We have developed a new wavelet-based technique that combines data from multiple stellar occultations (observed by the Visual and Infrared Mapping Spectrometer (VIMS) instrument onboard the Cassini spacecraft) that has allowed us to identify signals that may be due to waves generated by three of the strongest resonances in the central and outer B ring. These wave signatures yield new estimates of the B-ring's mass density and indicate that the B-ring's total mass could be quite low, perhaps a fraction of the mass of Saturn's moon Mimas.

Author(s): Matthew M. Hedman[2], Philip D. Nicholson[1]
Institution(s): *1. Cornell University, 2. University of Idaho*

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201 – New Approaches to Classical Dynamical Problems I

201.01 – Invited Talk: Modeling relativistic orbits and gravitational waves

Solving the relativistic two-body problem is difficult. Motivated by the construction, operation, and recent upgrades of interferometric gravitational-wave detectors, significant progress on this problem has been achieved over the past two decades. I will provide a summary of techniques that have been developed to solve the relativistic two-body problem, with an emphasis on semi-analytic approaches, their relevance to gravitational-wave astronomy, and remaining unsolved issues.

Author(s): Marc Favata[1]
Institution(s): *1. Montclair State University*

201.02 – Invited Talk: Instabilities in near-keplerian systems

Closed orbits drive secular gravitational instabilities, and Kepler potentials are one of only two potentials in which bound orbits are closed. Though the Kepler potential is common in astrophysics -- relevant for stars orbiting massive black holes in the centers of galaxies, for planets orbiting stars, and for moons orbiting planets — few instabilities have been explored beyond the linear regime in this potential. I will present two new instabilities which grow exponentially from small initial perturbations and act to reorient eccentric orbits in near-Keplerian disks. The first results from forces in the plane of the disk and acts to spread orbits in eccentricity. The second instability results from forces out of the disk plane and drives orbits to high inclination. I will explain the dynamical mechanism behind each and make observational predictions for both planetary systems and galactic nuclei.

Author(s): Anne-Marie Madigan[1]
Institution(s): *1. University of California*

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202 – New Approaches to Classical Dynamical Problems II

202.01 – The family of Quasi-satellite periodic orbits in the co-planar RTBP

In the framework of the Restricted Three-body Problem (RTBP), we consider a primary whose mass is equal to one, a secondary on circular or eccentric motion with a mass ε and a massless third body. The three bodies are in coplanar motion and in co-orbital resonance.
We actually know three classes of regular co-orbital motions: in rotating frame with the secondary, the tadpole orbits (TP) librate around Lagrangian equilibria L^4 or L^5; the horseshoe orbits (HS) encompass the three equilibrium points L^3, L^4 and L^5; the quasi-satellite orbits (QS) are remote retrograde satellite around the secondary, but outside of its Hill sphere.

Contrarily to TP orbits which emerge from a fixed point in rotating frame, QS orbits emanate from a one-parameter family of periodic orbits, denoted family-f by Henon (1969). In the averaged problem, this family can be understood as a family of fixed points. However, the eccentricity of these orbits can reach high values. Consequently a development in eccentricity will not be efficient.
Using the method developed by Nesvorný et al. (2002) which is valid for every values of eccentricity, we study the QS periodic orbits family with a numerical averaging.

In the circular case, I will present the validity domain of the average approximation and a particular orbit. Then, I will highlight an unexpected result for very high eccentricity on families of periodic orbits that originate from L^3, L^4 and L^5. Finally, I will sketch out an analytic method adapted to QS motion and exhibit associated results in the eccentric case.

Author(s): Alexandre Pousse[1], Philippe Robutel[1], Alain Vienne[1]
Institution(s): *1. IMCCE - Observatoire de Paris*

202.02 – End-State Relative Equilibria in the Sphere-Restricted Full Three-Body Problem

The Sphere-Restricted Full Three-Body Problem studies the motion of three finite density spheres as they interact under surface and gravitational forces. When accounting for the dissipation of energy, full-body systems may achieve minimum energy states that are unatainable in the classic treatment of the N-Body Problem. This serves as a simple model for the mechanics of rubble pile asteroids, interacting grains in a protoplanetary disk, and potentially the interactions of planetary ring particles. Previous studies of this problem have been performed in the case where the three spheres are of equal size and mass, with all possible relative equilibria and their stability having been identified as a function of the total angular momentum of the system. These studies uncovered that at certain levels of angular momentum there exists more than one stable relative equilibrium state. Thus a question of interest is which of these states a dissipative system would preferentially settle in provided some domain of initial conditions, and whether this would be a function of the dissipation parameters. Using perfectly-rigid dynamics, three-equal-sphere systems are simulated in a purpose-written C-based code to uncover these details. Results from this study are relevant to the mechanics and dynamics in small solar system bodies where relative forces are not great enough to compromise the rigidity of the constituents.

Author(s): Travis SJ Gabriel[1], Daniel J. Scheeres[1]
Institution(s): *1. University of Colorado Boulder*

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203 – Dynamical Constraints from Exoplanet Observations I

203.01 – Dynamical Evolution of planets in α Centauri AB

Circumstellar planets within α Centauri AB have been suggested through formation models (Quintana et al. 2002) and recent observations (Demusque et al. 2012). Driven by a new mission concept that will attempt to directly image Earth-sized planets, ACESat (Belikov et al. 2015), we revisit their possible existence through simulations of orbital stability that are far more comprehensive than were feasible by Wiegert and Holman (1997). We evaluate the stability boundary of Earth-like planets within α Centauri AB and elucidate some of the necessary observational constraints relative to the sky plane to directly image Earth-like planets orbiting either stellar component. We confirm the qualitative results of Wiegert and Holman regarding the approximate size of the regions of stable orbits and find that mean motion resonances with the stellar companion leave an imprint on the limits of orbital stability. Additionally, we discuss the differences in the extent of the imprint when considering both prograde and retrograde motions relative to the binary plane.

Author(s): Billy L. Quarles[1], Jack J. Lissauer[1]
Institution(s): *1. NASA Ames Research Center*

203.02 – Dynamical stability of imaged planetary systems in formation: Application to HL Tau

A recent ALMA image revealed several concentric gaps in the protoplanetary disk surrounding the young star HL Tau. We consider the hypothesis that these gaps are carved by planets, and present a general framework for understanding the dynamical stability of such systems over typical disk lifetimes, providing estimates for the maximum planetary masses. We argue that the locations of resonances should be significantly shifted in disks as massive as estimated for HL Tau, and that theoretical uncertainties in the exact offset, together with observational errors, imply a large uncertainty in the dynamical state and stability in such disks. An important observational avenue to breaking this degeneracy is to search for eccentric gaps, which could implicate resonantly interacting planets. Unfortunately, massive disks should also induce swift pericenter precession that would smear out any such eccentric features of planetary origin. This motivates pushing toward more typical, less massive disks. For a nominal non-resonant model of the HL Tau system with five planets, we find a maximum mass for the outer three bodies of approximately 2 Neptune masses. In a resonant configuration, these planets can reach at least the mass of Saturn. The inner two planets' masses are unconstrained by dynamical stability arguments.

Author(s): Daniel Tamayo[1], Amaury H.M.J. Triaud[1], Kristen Menou[1], Hanno Rein[1]
Institution(s): *1. University of Toronto at Scarborough*

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204 – Dynamical Constraints from Exoplanet Observations II

204.01 – Dynamical Analysis of the 6:1 Resonance of the Brown Dwarfs Orbiting the K Giant Star ν Ophiuchi

The K giant star ν Oph has two brown dwarf companions (with minimum masses of about 22 and 25 times the mass of Jupiter), whose orbital periods are about 530 and 3200 days and close to 6:1 in ratio. We present a dynamical analysis of this system, using 150 precise radial velocities obtained at the Lick Observatory in combination with data already available in the literature. We investigate a large set of orbital fits by applying systematic χ^2 grid-search techniques coupled with self-consistent dynamical fitting. We find that the brown dwarfs are indeed locked in an aligned 6:1 resonant configuration, with all six mean-motion resonance angles librating around 0°, but the inclination of the orbits is poorly constrained. As with resonant planet pairs, the brown dwarfs in this system were most likely captured into resonance through disk-induced convergent migration. Thus the ν Oph system shows that brown dwarfs can form like planets in disks around stars.

This work is supported in part by Hong Kong RGC grant HKU 7024/13P.

Author(s): Man Hoi Lee[2], Trifon Trifonov[2], Andreas Quirrenbach[1], Sabine Reffert[1]
Institution(s): *1. Landessternwarte, 2. The University of Hong Kong*

204.02 – Measurement of planet masses with transit timing variations due to synodic “chopping” effects

Gravitational interactions between planets in transiting exoplanetary systems lead to variations in the times of transit (TTVs) that are diagnostic of the planetary masses and the dynamical state of the system. I will present analytic formulae for TTVs which can be applied to pairs of planets on nearly circular orbits which are not caught in a mean motion resonance. For a number of Kepler systems with TTVs, I will show that synodic “chopping” contributions to the TTVs can be used to uniquely measure the masses of planets without full dynamical analyses involving direct integration of the equations of motion. This demonstrates how mass measurements from TTVs may primarily arise from an observable chopping signal. I will also explain our extension of these formulae to first order in eccentricity, which allows us to apply the formulae to pairs of planets closer to mean motion resonances and with larger eccentricities.

Author(s): Katherine Deck[1], Eric Agol[2]
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204.03 – Dialing the Love Number of Hot Jupiter HAT-P-13b

HAT-P-13b is Jupiter-mass transiting planet in a 0.04 AU orbit around its host star. It has an outer companion, HAT-P-13c, with a minimum mass of 14.7 MJup in a highly eccentric 1.2 AU orbit. These two companions form an isolated dynamical system with their host star [1]. The nature of this system allows the two bodies to settle into a fixed eccentricity state where the eccentricity of HAT-P-13b is directly related to its oblateness as described by the Love number, k2 [2]. In order to constrain the eccentricity, and therefore k2, of HAT-P-13b, we use the Spitzer Space Telescope to measure the timing of its secondary eclipses at 3.6 and 4.5 μm. We then simultaneously fit our secondary eclipse data in conjunction with previously measured radial velocity and transit data. Finally, we apply the fact that, if the orbits of HAT-P-13b and HAT-P-13c are coplanar, then their apsides are aligned [3]. The apsidal orientation of HAT-P-13c is much better constrained because of its high eccentricity, which helps break the degeneracy between the eccentricity and apsidal orientation in interpreting the measured secondary eclipse time. Our analysis allows us to measure the eccentricity of HAT-P-13b’s orbit with a precision approximately ten times better than that of previously published values, in the coplanar case, and allows us to place the first meaningful constraints on the core mass of HAT-P-13b.
[1] Becker & Batygin 2013, ApJ 778, 100 [2] Wu & Goldreich 2002, ApJ 564, 1024 [3] Batygin+ 2009, ApJ 704, L49

Author(s): Peter Buhler[1]
Institution(s): *1. Caltech*

205 – Dynamics of Small Solar System Bodies (moved early due to schedule conflict)

205.01 – High precision comet trajectory estimates: the Mars flyby of C/2013 A1 (Siding Spring)

The Mars flyby of C/2013 A1 (Siding Spring) represented a unique opportunity for imaging a long-period comet and resolving its nucleus and rotation period. Because of the small encounter distance and the high relative velocity, the goal of successfully observing C/2013 A1 from the Mars orbiting spacecrafts posed strict requirements on the accuracy of the comet ephemeris estimate. These requirements were hard to meet, as comets are known for being highly unpredictable: astrometric observations can be significantly biased and nongravitational perturbations significantly affect the trajectory. Therefore, we remeasured a couple of hundred astrometric positions from images provided by ground-based observers and also observed the comet with the Mars Reconnaissance Orbiter's HiRISE camera on 2014 October 7. In particular, the HiRISE observations were decisive in securing the trajectory and revealed that nongravitational perturbations were larger than anticipated. The comet was successfully observed and the analysis of the science data is still ongoing. By adding some post-encounter data and using the Rotating Jet Model for nongravitational accelerations we constrain the rotation pole of C/2013 A1.

Author(s): Davide Farnocchia[5], Steven R. Chesley[5], Marco Micheli[3], Alan Delamere[2], Leslie Tamppari[5], David J. Tholen[4], Rodney S. Heyd[6], William M. Owen[5], Jon D. Giorgini[5], Jian-Yang Li[7], Casey M. Lisse[1]
Institution(s): *1. APL, Johns Hopkins University, 2. Delamere Support Services, 3. ESA NEOCC, 4. IfA, University of Hawaii, 5. JPL, Caltech, 6. PIRL, University of Arizona, 7. PSI*

300 – Dynamics of Small Solar System Bodies I

300.01 – The 2014 KCG meteor outburst: clues to a parent body

The κ Cygnid (KCG) meteor shower exhibited unusually high activity in 2014, producing ten times the typical number of meteors. The shower was detected in both radar and optical systems and meteoroids associated with the outburst spanned at least five decades in mass. In total, the Canadian Meteor Orbit Radar, European Network, and NASA All Sky and Southern Ontario Meteor Network produced thousands of KCG meteor trajectories. Using these data, we have undertaken a new and improved characterization of the dynamics of this little-studied, variable meteor shower. The κ Cygnids have a diffuse radiant and a significant spread in orbital characteristics, with multiple resonances appearing to play a role in the shower dynamics. We conducted a new search for parent bodies and found that several known asteroids are orbitally similar to the KCGs. N-body simulations show that the two best parent body candidates readily transfer meteoroids to the Earth in recent centuries, but neither produces an exact match to the KCG radiant, velocity, and solar longitude. We nevertheless identify asteroid 2001 MG1 as a promising parent body candidate.

Author(s): Althea V Moorhead[3], Peter G. Brown[2], Pavel Spurný[1], William Cooke[3]
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300.02 – Increasing Space Situational Awareness for NEOs

Over the past years, Europe has strengthened its commitment to foster space situational awareness. Apart from the current efforts in tracking space weather, artificial satellites and space debris, Near Earth Asteroid threat assessment is a key task. NEOshield has been part of this European effort. We will give an overview over national projects and European programs with French participation such as PoDET, ESTERS, FRIPON, NEOShield, Gaia-FUN-SSO and Stardust. Future plans regarding Near Earth Object threat assessment and mitigation are described. The role of the IMCCE in this framework is discussed using the example of the post mitigation impact risk analyis of Gravity Tractor and Kinetic Impactor based asteroid deflection demonstration mission designs.

Author(s): Daniel J.G.J. Hestroffer[1], Siegfried Eggl[1], William Thuillot[1]
Institution(s): *1. IMCCE/Paris observatory*

300.03 – The onset of dynamical instability and chaos in navigation satellite orbits

Orbital resonances are ubiquitous in the Solar System and are harbingers for the onset of dynamical instability and chaos. It has long been suspected that the Global Navigation Satellite Systems exist in a background of complex resonances and chaotic motion; yet, the precise dynamical character of these phenomena remains elusive. Here we will show that the same underlying physical mechanism, the overlapping of secular resonances, responsible for the eventual destabilization of Mercury and recently proposed to explain the orbital architecture of extrasolar planetary systems (Lithwick Y., Wu Y., 2014, PNAS; Batygin K., Morbidelli A., Holman M.J., 2015, ApJ) is at the heart of the orbital instabilities of seemingly more mundane celestial bodies---the Earth's navigation satellites. We will demonstrate that the occurrence and nature of the secular resonances driving these dynamics depend chiefly on one aspect of the Moon's perturbed motion, the regression of the line of nodes. This talk will present analytical models that accurately reflect the true nature of the resonant interactions, and will show how chaotic diffusion is mediated by the web-like structure of secular resonances. We will also present an atlas of FLI stability maps, showing the extent of the chaotic regions of the phase space, computed through a hierarchy of more realistic, and more complicated, models, and compare the chaotic zones in these charts with the analytical estimation of the width of the chaotic layers from the heuristic Chirikov resonance-overlap criterion. The obtained results have remarkable practical applications for space debris mitigation and for satellite technology, and are both of essential dynamical and theoretical importance, with broad implications for planetary science.

Author(s): Aaron Jay Rosengren[2], Jérôme Daquin[4], Elisa Maria Alessi[2], Giovanni B. Valsecchi[1], Alessandro Rossi[2], Florent Deleflie[3]
Institution(s): *1. IAPS-INAF, 2. IFAC-CNR, 3. IMCCE/Observatoire de Paris, 4. Thales Servies*

300.04 – The Evolution of the Grand Tack's Main Belt through the Solar System's Age

The Asteroid Belt is marked by the mixture of physical properties among its members, as well as its peculiar distribution of orbital eccentricities and inclinations. Formation models of the Asteroid Belt show that its formation is strongly linked to the process of terrestrial planet formation. The Grand Tack model presents a possible solution to the conundrum of reconciling the small mass of Mars with the properties of the Asteroid Belt, providing also a scenario for understanding the mixture of physical properties of the Belt objects. Regarding the orbital distribution of these objects, the Grand Tack model achieved good agreement with the observed inclination distribution, but failed in relation to the eccentricities, which are systematically skewed towards too large values at the end of the dynamical phase described by the Grand Tack model. Here, we evaluate the evolution of the orbital characteristics of the Asteroid Belt from the end of the phase described by the Grand Tack model, throughout the subsequent evolution of the Solar System. Our results show the concrete possibility that the eccentricity distribution after the Grand Tack phase is consistent with the current distribution. Finally, favorable and unfavorable issues faced by the Grand Tack model will be discussed, together with the influence of the primordial eccentricities of Jupiter and Saturn. Acknowledgement: FAPESP.

Author(s): Rogerio Deienno[2], Rodney S. Gomes[3], Alessandro Morbidelli[1], Kevin J. Walsh[4], David Nesvorny[4]
Institution(s): *1. Laboratorie Lagrange, OCA, 2. National Institute for Space Research, 3. National Observatory, 4. Southwest Research Institute*

300.05 – The Evidence for Slow Migration of Neptune from the Inclination Distribution of Kuiper Belt Objects

Much of the dynamical structure of the Kuiper Belt can be explained if Neptune migrated over several AU, and/or if Neptune was scattered to an eccentric orbit during planetary instability. An outstanding problem with the existing formation models is that the distribution of orbital inclinations predicted by them is narrower than the one inferred from observations. Here we perform numerical simulations of the Kuiper belt formation starting from an initial state with Neptune at $20<a^{N,0}<30$ AU and a dynamically cold outer disk extending from beyond $a^{N,0}$ to 30 AU. Neptune's orbit is migrated into the disk on an e-folding timescale $1\leq\tau\leq100$ Myr. A small fraction ($\sim10^{-3}$) of disk planetesimals become implanted into the Kuiper belt in the simulations. By analyzing the orbital distribution of the implanted bodies in different cases we find that the inclination constraint implies that $\tau\geq10$ Myr and $a^{N,0}\leq26$ AU.The models with $τ<10 Myr do not satisfy the inclination constraint, because there is not enough time for various dynamical processes to raise inclinations. The slow migration of Neptune is consistent with other Kuiper belt constraints, and with the recently developed models of planetary instability/migration. Neptune's eccentricity and inclination are never large in these models ($e^N<0.1$, $i^N<2$ deg), as required to avoid excessive orbital excitation in the >40 AU region, where the Cold Classicals presumably formed.

Author(s): David Nesvorny[1]
Institution(s): *1. SWRI*

301 – Dynamics of Small Solar System Bodies II

301.01 – Gravity and Tide Parameters Determined from Satellite and Spacecraft Orbits

As part of our work on the development of the Jovian and Saturnian satellite ephemerides to support the *Juno* and *Cassini* missions, we determined a number of planetary system gravity parameters. This work did not take into account tidal forces. In fact, we saw no obvious observational evidence of tidal effects on the satellite or spacecraft orbits. However, Lainey et al. (2009 Nature **459**, 957) and Lainey et. al (2012 Astrophys. J. **752**, 14) have published investigations of tidal effects in the Jovian and Saturnian systems, respectively. Consequently, we have begun a re-examination of our ephemeris work that includes a model for tides raised on the planet by the satellites as well as tides raised on the satellites by the planet. In this paper we briefly review the observations used in our ephemeris production; they include astrometry from the late 1800s to 2014, mutual events, eclipses, occultatons, and data acquired by the *Pioneer, Voyager, Ulysses, Cassini, Galileo,* and *New Horizons* spacecraft. We summarize the gravity parameter values found from our original analyses. Next we discuss our tidal acceleration model and its impact on the gravity parameter determination. We conclude with preliminary results found when the reprocessing of the observations includes tidal forces acting on the satellites and spacecraft.

Author(s): Robert A. Jacobson[1]
Institution(s): *1. JPL*

301.03 – Contact Binary Asteroids

Recent observations have found that some contact binaries are oriented such that the secondary impacts with the primary at a high inclination. This research investigates the evolution of how such contact binaries came to exist. This process begins with an asteroid pair, where the secondary lies on the Laplace plane. The Laplace plane is a plane normal to the axis about which the pole of a satellites orbit precesses, causing a near constant inclination for such an orbit. For the study of the classical Laplace plane, the secondary asteroid is in circular orbit around an oblate primary with axial tilt. This system is also orbiting the Sun. Thus, there are two perturbations on the secondarys orbit: J2 and third body Sun perturbations. The Laplace surface is defined as the group of orbits that lie on the Laplace plane at varying distances from the primary. If the secondary is very close to the primary, the inclination of the Laplace plane will be near the equator of the asteroid, while further from the primary the inclination will be similar to the asteroid-Sun plane. The secondary will lie on the Laplace plane because near the asteroid the Laplace plane is stable to large deviations in motion, causing the asteroid to come to rest in this orbit. Assuming the secondary is asymmetrical in shape and the bodys rotation is synchronous with its orbit, the secondary will experience the BYORP effect. BYORP can cause secular motion such as the semi-major axis of the secondary expanding or contracting. Assuming the secondary expands due to BYORP, the secondary will eventually reach the unstable region of the Laplace plane. The unstable region exists if the primary has an obliquity of 68.875 degrees or greater. The unstable region exists at 0.9 Laplace radius to 1.25 Laplace radius, where the Laplace radius is defined as the distance from the central body where the inclination of the Laplace plane orbit is half the obliquity. In the unstable region, the eccentricity of the orbit increases. Once the eccentricity becomes very large or approaching 1, the orbit of the secondary intersects with the primary and will eventually collide and becomes a contact binary.

Author(s): Samantha Rieger[1]
Institution(s): *1. University of Colorado*

301.04 – Stochastic YORP On Real Asteroid Shapes

Since its theoretical foundation and subsequent observational verification, the YORP effect has been understood to be a fundamental process that controls the evolution of small asteroids in the inner solar system. In particular, the coupling of the YORP and Yarkovsky effects are hypothesized to be largely responsible for the transport of asteroids from the main belt to the inner solar system populations. Furthermore, the YORP effect is thought to lead to rotational fission of small asteroids, which leads to the creation of multiple asteroid systems, contact binary asteroids, and asteroid pairs. However recent studies have called into question the ability of YORP to produce these results. In particular, the high sensitivity of the YORP coefficients to variations in the shape of an asteroid, combined with the possibility of a changing shape due to YORP accelerated spin rates can combine to create a stochastic YORP coefficient which can arrest or change the evolution of a small asteroid’s spin state. In this talk, initial results are presented from new simulations which comprehensively model the stochastic YORP process. Shape change is governed by the surface slopes on radar based asteroid shape models, where the highest slope regions change first. The investigation of the modification of YORP coefficients and subsequent spin state evolution as a result of this dynamically influenced shape change is presented and discussed.

Author(s): Jay W. McMahon[1]
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301.05 – New Trans-Neptunian Objects in the Dark Energy Survey Supernova Fields

The Dark Energy Survey (DES) observes ten separate 3 sq. deg. fields approximately weekly for six months each year. Although intended primarily to detect Type Ia supernovae, this data set provides a rich time series that is well suited for the detection of objects in the outer solar system, which move slowly enough that they can remain in the same field of view for weeks, months, or even across multiple DES observing seasons. Because the supernova fields have ecliptic latitudes ranging from -15 to -45 degrees, DES is particularly sensitive to the dynamically hot population of Kuiper Belt objects, as well as detached/inner Oort cloud objects. Here I report the results of a search for new trans-Neptunian objects in the first two seasons of DES data, to limiting magnitudes of r~23.8 in the eight shallow fields and ~24.5 in the two deep fields. The 22 objects discovered to date include two new Neptune trojans, a number of objects in mean motion resonances with Neptune, two objects with orbital inclinations above 45 degrees, a Uranian resonator, and several distant scattered disk objects including one with an orbital period of nearly 6000 years. This latter object is among the half-dozen longest-period trans-Neptunian objects known, and like the other such objects has an argument of perihelion near zero degrees. I will discuss the properties and orbital dynamics of objects discovered to date, and will also discuss prospects for extending the search to the full 5000 sq. deg. DES wide survey.

Author(s): David W. Gerdes[1]
Institution(s): *1. University of Michigan*

302 – Dynamics of Small Solar System Bodies III

302.01 – Lense-Thirring Effect Measurement from LAGEOS Node: Limitation from Radiation Forces

The Lense-Thirring (L-T) effect from General Relativity predicts a small secular increase to the node right ascension for close Earth satellites. For the LAGEOS 1 satellite, the predicted node increase is 31 mas/y. There is a current effort to observationally evaluate L-T to 1 percent accuracy through an orbit analysis of the laser-ranged LAGEOS 1, LAGEOS 2, and LARES satellites. Uncertainty in the computed gravitational perturbations to the satellite nodes, due to parameter uncertainties, is largely eliminated by taking a linear combination of the node positions which eliminates the uncertainty due to the major terms. One then looks for the L-T effect on this composite node.

But there remains uncertainty in the computed perturbations due to two radiation (non-gravitational) forces: the solar radiation (SR) force and thermal thrust (Yarkovsky effects). This paper treats LAGEOS 1 perturbations. For simplicity in discussion, we treat perturbations to its node rather than perturbations to the composite node.

Uncertainty in the perturbation rates arises from ignorance of parameter values for the LAGEOS 1 exterior aluminum surface, specifically, the solar absorbtance and thermal emittance. The LAGEOS 1 Phase B design study proposed three different sets of aluminum surface parameters without recommending a particular set. The LAGEOS 1 as-built surface parameters were not measured prior to spacecraft launch.

The possible spread in LAGEOS 1 solar absorbtance values gives a spread of ±0.42 mas/y in the SR force contribution to its node rate. This results in a ±1.3 percent uncertainty to the L-T determination. But because of its long-period perturbation to the eccentricity vector, evaluating the SR force parameter as a solved-for parameter in the orbit analysis should significantly reduce the uncertainty in the corresponding node motion.

The possible spread in LAGEOS 1 surface values gives a spread of ±0.16 mas/y in the thermal thrust contribution to its node rate. This represents a ±0.53 percent uncertainty in the L-T determination which leaves little room for other error sources. Ground-based satellite brightness measurements could improve knowledge of the surface absorbtance and reduce the uncertainty from thermal thrust.

Author(s): Victor J. Slabinski[1]
Institution(s): *1. U.S. Naval Observatory*

303 – Star Cluster Dynamics

303.01 – Invited Talk: Dynamical Evolution of Multiple-Population Globular Clusters

Numerous spectroscopic and photometric studies have provided strong evidence of the presence of multiple stellar populations in globular clusters and raised many fundamental questions concerning the formation and dynamical evolution of these stellar systems. After a brief review of the main observational studies, I will present the results of theoretical investigations exploring a number of aspects of the internal dynamics of multiple-population clusters and their formation history.

Author(s): Enrico Vesperini[1]
Institution(s): *1. Indiana University*

303.02 – Cross Sections for Planetary Systems Interacting with Passing Stars and Binaries

Most planetary systems are formed within stellar clusters, and these environments can shape their properties. This talk considers scattering encounters between solar systems and passing cluster members, and calculates the corresponding interaction cross sections. The target solar systems are generally assumed to have four giant planets, with a variety of starting states, including circular orbits with the semimajor axes of our planets, a more compact configuration, an ultra-compact state with multiple mean motion resonances, and systems with massive planets. We then consider the effects of varying the cluster velocity dispersion, the relative importance of binaries versus single stars, different stellar host masses, and finite starting eccentricities of the planetary orbits. For each state of the initial system, we perform an ensemble of numerical scattering experiments and determine the cross sections for eccentricity increase, inclination angle increase, planet ejection, and capture. This talk reports results from over 2 million individual scattering simulations. Using supporting analytic considerations, and fitting functions to the numerical results, we find a universal formula that gives the cross sections as a function of stellar host mass, cluster velocity dispersion, starting planetary orbital radius, and final eccentricity. The resulting cross sections can be used in a wide variety of applications. As one example, we revisit constraints on the birth aggregate of our Solar System due to dynamical scattering and find N < 10,000 (consistent with previous estimates).

Author(s): Fred C. Adams[2], Gongjie Li[1]
Institution(s): *1. Center for Astrophysics, 2. University of Michigan*

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304 – Moon Formation and Dynamics I

304.01 – Recent Formation of Saturnian Moons: Constraints from Their Cratering Records

Charnoz et al. (2010) proposed that Saturn's small "ring moons" out to Janus and Epimetheus consist of ring material that viscously spread beyond the Roche limit and coagulated into moonlets. The moonlets evolve outward due to the torques they exert at resonances in the rings. More massive moonlets migrate faster; orbits can cross and bodies can merge, resulting in a steep trend of mass vs. distance from the planet. Canup (2010) theorized that Saturn's rings are primordial and originated when a differentiated, Titan-like moon migrated inward when the planet was still surrounded by a gas disk. The satellite's icy shell could have been tidally stripped, and would have given rise to today's rings and the mid-sized moons out to Tethys. Charnoz et al. (2011) investigated the formation of satellites out to Rhea from a spreading massive ring, and Crida and Charnoz (2012) extended this scenario to other planets. Once the mid-sized moons recede far from the rings, tidal interaction with the planet determines the rate at which the satellites migrate. Charnoz et al. (2011) found that Mimas would have formed about 1 billion years more recently than Rhea. The cratering records of these moons (Kirchoff and Schenk 2010; Robbins et al. 2015) provide a test of this scenario. If the mid-sized moons are primordial, most of their craters were created through hypervelocity impacts by ecliptic comets from the Kuiper Belt/Scattered Disk (Zahnle et al. 2003; Dones et al. 2009). In the Charnoz et al. scenario, the oldest craters on the moons would result from low-speed accretionary impacts. We thank the Cassini Data Analysis program for support.

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Author(s): Henry C. (Luke) Dones[3], Sebastien Charnoz[1], Stuart J. Robbins[3], Edward B. Bierhaus[2]
Institution(s): *1. Institut de Physique du Globe, 2. Lockheed Martin Space Systems Company, 3. Southwest Research Institute*

304.02 – Constraints on Titan's rotation from Cassini mission radar data

We present results of a new analysis of the rotational kinematics of Titan, as constrained by Cassini radar data, extending over the entire currently available set of flyby encounters. Our analysis provides a good constraint on the current orientation of the spin pole, but does not have sufficient accuracy and duration to clearly see the expected spin pole precession. In contrast, we do clearly see temporal variations in the spin rate, which are driven by gravitational torques which attempt to keep the prime meridian oriented toward Saturn.

Titan is a synchronous rotator. At lowest order, that means that the rotational and orbital motions are synchronized. At the level of accuracy required to fit the Cassini radar data, we can see that synchronous rotation and uniform rotation are not quite the same thing. Our best fitting model has a fixed pole, and a rotation rate which varies with time, so as to keep Titan’s prime meridian oriented towards Saturn, as the orbit varies.

A gravitational torque on the tri-axial figure of Titan attempts to keep the axis of least inertia oriented toward Saturn. The main effect is to synchronize the orbit and rotation periods, as seen in inertial space. The response of the rotation angle, to periodic changes in orbital mean longitude, is modeled as a damped, forced harmonic oscillator. This acts as a low-pass filter. The rotation angle accurately tracks orbital variations at periods longer than the free libration period, but is unable to follow higher frequency variations.

The mean longitude of Titan's orbit varies on a wide range of time scales. The largest variations are at Saturn's orbital period (29.46 years), and are due to solar torques. There are also variations at periods of 640 and 5800 days, due to resonant interaction with Hyperion.

For a rigid body, with moments of inertia estimated from observed gravity, the free libration period for Titan would be 850 days. The best fit to the radar data is obtained with a libration period of 645 days, and a damping time of 1000 years.

The principal deviation of Titan's rotation from uniform angular rate, as seen in the Cassini radar data, is a periodic signal resonantly forced by Hyperion.

Author(s): Bruce Bills[2], Bryan W. Stiles[2], Alexander Hayes[1]
Institution(s): *1. Cornell University, 2. Jet Propulsion Laboratory*

304.03 – Forced libration of tidally synchronized planets and moons

Tidal dissipation of kinetic energy, when it is strong enough, tends to synchronize the rotation of planets and moons with the mean orbital motion, or drive it into long-term stable spin-orbit resonances. As the actual orbital motion undergoes periodic acceleration due to a finite orbital eccentricity, the spin rate oscillates around the equilibrium mean value too, giving rise to the forced, or eccentricity-driven, librations. We contend that both the shape and amplitude of forced librations of synchronous viscoelastic planets and moons are defined by a combination of two different types of perturbative torque, the tidal torque and the triaxial torque, the latter related to a permanent deformation of the distribution of mass from a perfect rotational symmetry. Consequently, forced librations can be tidally dominated (e.g., Io and possibly Titan) or deformation-dominated (e.g., the Moon) depending on a set of orbital, rheological, and other physical parameters. With small eccentricities, for the former kind, the largest term in the libration angle can be minus cosine of the mean anomaly, whereas for the latter kind, it is minus sine of the mean anomaly. The shape and the amplitude of tidal forced librations determine the rate of orbital evolution of synchronous planets and moons, i.e., the rate of dissipative damping of the semimajor axis and eccentricity. The known super-Earth exoplanets can exhibit both kinds of libration, or a mixture of thereof, depending on, for example, the effective Maxwell time of their rigid mantles. Our approach can be extended to estimate the amplitudes of other libration harmonics, as well as the forced libration in non-synchronous spin-orbit resonances.

Author(s): Bryan Dorland[1], Valeri V Makarov[1]
Institution(s): *1. US Naval Observatory*

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305 – Poster Session

305.01 – Stable Configurations of the υ Andromedae Planetary System

The υ Andromedae system is the first exoplanetary system to have the relative inclinations of two planets' orbital planes directly measured (McArthur et al. 2010), and therefore offers our first window into the 3-dimensional configurations of planetary systems. We present a full 3-dimensional, dynamically stable configuration for the 3 planets of the system, following up on McArthur et al (2010), which revealed that the orbits of the outer 2 planets are inclined by 30 deg. We used N-body simulations to search for stable 3-planet configurations that are consistent with the combined radial velocity and astrometric solution. The inner-most planet, b, could have only been detected by HST astrometry if it was at extremely low inclination. Because of this, its true mass and orbital plane are unconstrained by the observations, but our stability analysis limits their ranges significantly.
The system appears to be close to the stability boundary, as we find that only 10 trials out of 1000 are robustly stable on 100 Myr timescales, or ~8 billion orbits of planet b. We find planet b's orbit must lie close to the fundamental plane of planets c and d, but can be either prograde or retrograde. These solutions predict b's mass is in the range 2 - 9 M^{Jup} and has an inclination angle from the sky plane of less than 45 deg. Crossfield et al. (2010) detected the planet via brightness variations in the combined light curve, and argued that such a configuration would require b's radius to be ~1.8 R^{Jup}, relatively large for a planet of its age. However, the eccentricity of b in several of our stable solutions reaches > 0.1, inducing upwards of 10^{19} watts in the interior of the planet via tidal dissipation. Ibgui et al. (2009) find that this energy source could inflate the radius to the amount required for Crossfield et al., and thus we have solutions that are

consistent with all observational constraints.
The Gaia telescope (Casertano et al. 2008) will refine the orbits of planets c and d and perhaps provide further constraints on b, such as a minimum inclination and maximum mass. Gaia will astrometrically determine the orbits of many other exoplanets, providing clues to the formation mechanisms and uniqueness of this system.

Author(s): Russell Deitrick[2], Rory Barnes[2], Barbara McArthur[1], Thomas R. Quinn[2], Rodrigo Luger[2], Adrienne Antonsen[2], G. Fritz Benedict[1]
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305.02 – High Precision Bright-Star Astrometry with the USNO Astrometric CMOS Hybrid Camera System

While GAIA will provide excellent positional measurements of hundreds of millions of stars between 5 < mag < 20, an ongoing challenge in the field of high-precision differential astrometry is the positional accuracy of very bright stars (mag < 5), due to the enormous dynamic range between bright stars of interest, such as those in the Hipparcos catalog, and their background field stars, which are especially important for differential astrometry. Over the past few years, we have been testing the USNO Astrometric CMOS Hybrid Camera System (UAHC), which utilizes an H4RG-10 detector in windowing mode, as a possible solution to the NOFS USNO Bright Star Astrometric Database (UBAD). In this work, we discuss the results of an astrometric analysis of single-epoch Hipparcos data taken with the UAHC from the 1.55m Kaj Strand Astrometric Reflector at NOFS from June 27-30, 2014. We discuss the calibration of this data, as well as an astrometric analysis pipeline we developed that will enable multi-epoch differential and absolute astrometry with the UAHC. We find that while the overall differential astrometric stability of data taken with the UAHC is good (5-10 mas single-measurement precision) and comparable to other ground-based astrometric camera systems, bright stars in the detector window suffer from several systematic effects, such as insufficient window geometry and centroiding failures due to read-out artifacts—both of which can be significantly improved with modifications to the electronics, read-out speed and microcode.

Author(s): Nathan Secrest[1], Rachel Dudik[1], Ciprian T. Berghea[1], Greg Hennessy[1], Bryan Dorland[1]
Institution(s): *1. US Naval Observatory*

305.03 – Synthetic Representation of the Motion of Co-orbitals of the Galilean Satellites

Two of Saturn's satellites (Tethys and Dione) each have two co-orbital companions at their L4 and L5 triangular equilibrium points. This prompts us to ask: do any of Jupiter's Galilean satellites have co-orbitals? In our analysis, the motions of the Galilean satellites are specified by the model E5 of Lieske, truncated to include the dominant terms. This model includes the oblate figure of Jupiter, mutual perturbations between pairs of satellites, and perturbations from Saturn and the Sun. The initial positions and velocities of co-orbital test particles are specified by a rotation of the state vector of the Galilean satellite with which it shares an orbit, on a reference date, through a given angle, and the equations of motion are integrated. Integrations are carried out for 100,000 days, which is several hundred times the longest forcing period. A linearized stability analysis of motion about the L4 or L5 Lagrange points, of the circular restricted three body problem, predicts oscillations in angular separation at two main frequencies. In the six body problem that we consider here, these same frequencies appear, along with characteristic families of harmonics. Numerically integrated co-orbitals trajectories in the rotating frame exhibit the expected tadpole behavior. The Fourier amplitude spectrum of the numerically integrated angular separation between the co-orbital and its parent satellite exhibits two sets of characteristic features. The first set consists of the prominent lines in the spectrum of the variability in satellite mean motion. The second consists of the restricted three body predicted frequencies, and the families of related spectral lines which emerge for pertrubations in the restricted problem. Our integrations suggest that the motion of co-orbitals of the Galilean satellites is well approximated by this simple scheme.

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305.04 – Aspects of Solar System Objects Dynamics with the Gaia Mission and in the Gaia Era

After its successful launch in December 2013, and commissioning period, ESA's astrometric space mission Gaia has now started its scientific operations. In addition to the 3D census of our Milky Way with high precision parallax, proper motion, and other parameters derived for a billion of stars, Gaia will also provide a scientific harvest for Solar System Objects (SSO) science. The high precision astrometry and photometry that will be regularly collected for about 300,000 asteroids–during the 5years nominal mission time–will enable significant improvements on fundamental observational data for a very large number of objects.
I will describe the current status of the satellite and observations, the Gaia-FUN-SSO follow-up network, data releases policy, and data validations. We will also present the expected results on the dynamics of asteroids and comets, asteroid masses and binary asteroids, tests of GR, and prospects of SSO science (satellites, stellar occultations, etc.) with the Gaia stellar catalogue.

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305.05 – Migration of two massive planets into (and out of) first order resonances

During the early stages of planetary system evolution, convergent migration of planet pairs typically leads to capture into resonance, provided that the dissipative resonance-crossing time is long compared with the libration timescale. In light of this, it is unclear why multi-transiting planetary systems found by the Kepler survey do not preferentially reside in mean-motion commensurabilities. As a potential resolution to this puzzle, it has been proposed (Goldreich and Schlicting 2014) that coupling between eccentricity damping and semi-major axis migration can lead to destabilization of resonances, hence reconciling the lack of resonant pairs found by Kepler with migration theories. We have extended this analysis to the realm of the unrestricted elliptic three-body problem to better understand for which parameters this destabilization can occur. Our results thus enable a more thorough evaluation of the capability of this mechanism to explain the existing observations.

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400 – Moon Formation and Dynamics II

400.01 – Recent dynamical evolution of Mimas and Enceladus

Mimas and Enceladus are the smallest and innermost mid-sized icy moons of Saturn. They are each caught in a 2:1 orbital resonance with an outer, larger moon: Mimas with Tethys, Enceladus with Dione. This is where the similarities end. Mimas is heavily cratered and appears geologically inactive, while Enceladus has a young surface and high tidal heat flow. Large free eccentricity of Mimas implies low tidal dissipation, while Enceladus appears very dissipative, likely due to an internal ocean. Their resonances are very different too. Mimas is caught in a 4:2 inclination type resonance with Tethys which involves inclinations of both moons. Enceladus is in a 2:1 resonance with Dione which affects only Enceladus's eccentricity. The well-known controversy over the heat flow of Enceladus can be solved by invoking a faster tidal evolution rate than previously expected (Lainey et al. 2012), but other mysteries remain. It has been long known that Mimas has very low probability of being captured into the present resonance, assuming that the large resonant libration amplitude reflects sizable pre-capture inclination of Mimas. Furthermore, Enceladus seems to have avoided capture into a number of sub-resonances that should have preceded the present one. An order of magnitude increase in the rate of tidal evolution does not solve these problems. It may be the time to reconsider the dominance of tides in the establishment of these resonances, especially if the moons themselves may be relatively young. An even faster orbital evolution due to ring/disk torques can help avoid capture into smaller resonances. Additionally, past interaction of Mimas with Janus and Epimetheus produce some of the peculiarities of Mimas' current orbit. At the meeting I will present numerical integrations that confirm the the existence of these problems, and demonstrate the proposed solutions.

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400.02 – Rotational and interior models for Enceladus

We will discuss the underlying dynamical models and the consequent interior models that pertain to our discovery of a forced rotational libration for Saturn's moon Enceladus (Thomas et al. 2015).

Despite orbital variations that change the mean motion on timescales of several years owing to mutual satellite interactions, the rotation state of Enceladus should remain synchronous with the varying mean motion, as long as damping is as expected (Tiscareno et al. 2009, Icarus). Taking that dynamically synchronous rotation as the ground state, we construct a model that naturally focuses on the physically interesting librations about the synchronous state that occur on orbital timescales. We will discuss the differences between the method used here and other dynamical methods (e.g., Rambaux et al. 2010, GRL; cf. Tajeddine et al. 2014, Science), and we will review the rotation states (whether known or predicted) of other moons of Saturn.

We will also describe our measurements of the control point network on the surface of Enceladus using Cassini images, which was then used to obtain its physical forced libration amplitude at the orbital frequency. The fit of Cassini data

results in a libration amplitude too large to be consistent with a rigid connection between the surface and the core, ruling out the simplest interior models (e.g., homogeneous, two-layer, two-layer with south polar anomaly). Alternatively, we suggest an interior model of Enceladus involving a global ocean that decouples the shell from the core, with a thinner icy layer in the south polar region as an explanation for both the libration (Thomas et al. 2015) and the gravity (Iess et al. 2014, Science) measurements.

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Institution(s): *1. Cornell Univ.*

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400.04 – On the in situ formation of Pluto's small satellites

The formation of Pluto's small satellites – Styx, Nix, Keberos and Hydra remains a mystery. Their orbits are nearly circular (eccentricity e = 0.0055 or less) and near resonances and coplanar with respect to Charon. One scenario suggests that they all formed close to their current locations from a disk of debris, which was ejected from the Charon-forming impact. We test the validity of this scenario by performing N-body simulations with Pluto-Charon evolving tidally from an initial orbit at a few Pluto radii. The small satellites are modeled as test particles with initial orbital distances within the range of the current small satellites and damped to their coldest orbits by collisional damping. It is found that if Charon is formed from a debris disk and has low initial eccentricity, all test particles survive to the end of the tidal evolution, but there is no preference for resonances and the test particles' final e is typically > 0.01. If Charon is formed in the preferred intact capture scenario and has initial orbital eccentricity ~ 0.2, the outcome depends on the relative rate of tidal dissipation in Charon and Pluto, A. If A is large and Charon's orbit circularizes quickly, a significant fraction of the test particles survives outside resonances with e >~ 0.01. Others are ejected by resonance or survive in resonance with very large e (> 0.1). If A is small and Charon's orbit remains eccentric throughout most of the tidal evolution, most of the test particles are ejected. The test particles that survive have e >~ 0.01, including some with e > 0.1. None of the above cases results in test particles with sufficiently low final e.

This work is supported in part by Hong Kong RGC grant HKU 7030/11P.

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400.05 – On the Spin-axis Dynamics of the Earth

The variation of a planet's obliquity is influenced by the existence of satellites with a high mass ratio. For instance, the Earth's obliquity is stabilized by the Moon, and would undergo chaotic variations in the Moon's absence. In turn, such variations can lead to large-scale changes in the atmospheric circulation, rendering spin-axis dynamics a central issue for understanding climate. The relevant quantity for dynamically-forced climate change is the rate of chaotic diffusion. Accordingly, here we reexamine the spin-axis evolution of a Moonless Earth within the context of a simplified perturbative framework. We present analytical estimates of the characteristic Lyapunov coefficient as well as the chaotic diffusion rate and demonstrate that even in absence of the Moon, the stochastic change in the Earth's obliquity is sufficiently slow to not preclude long-term habitability. Our calculations are consistent with published numerical experiments and illustrate the putative system's underlying dynamical structure in a simple and intuitive manner. In addition, we examine if at any point in the Earth's evolutionary history, the obliquity varied significantly. We find that even though the orbital perturbations were different in the past, the system nevertheless avoided resonant encounters throughout its evolution. This indicates that the Earth obtained its current obliquity during the formation of the Moon.

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401 – Galaxy Dynamics

401.02 – p-ellipse Orbit Approximations, Lindblad Zones, and Resonant Waves in Galaxy Disks

p-ellipses are simple, yet very accurate formulae for orbits in power-law potentials, like those approximating galaxy disks. These precessing elliptical orbits reveal important systematics of orbits in such potentials, including simple expressions for the dependence of apsidal precession on eccentricity, and the fact that very few terms (or parameters) are needed for the approximation of even nearly radial orbits. The orbit approximations are also useful tools for addressing problems in galaxy dynamics. In particular, they indicate the existence of a range of eccentric resonances associated with the usual, near-circular Lindblad resonances. Collectively these change an isolated Lindblad resonance to a Lindblad Zone of eccentric resonances. A range of these resonances could be excited at a common pattern speed, aiding the formation of a variety of bars and spirals, out of eccentric orbits. Such waves would be persistent, and not wind up or disperse, since differences in their precession frequencies offset differences in the circular velocities at the radii of their parent orbits. The p-ellipse approximation further reveals how a non-axisymmetric component of the gravitational potential (e.g., due to bar self-gravity) significantly modifies precession frequencies, and similarly modifies the Lindblad Zones.

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401.03 – Bars Triggered By Galaxy Flybys

Galaxy mergers drive galaxy evolution and are a key mechanism by which galaxies grow and transform. Unlike galaxy mergers where two galaxies combine into one remnant, galaxy flybys occur when two independent galaxy halos interpenetrate but detach at a later time; these one-time events are surprisingly common and can even out-number galaxy mergers at low redshift for massive halos. Although these interactions are transient and occur far outside the galaxy disk, flybys can still drive a rapid and large pertubations within both the intruder and victim halos. We explored how flyby encounters can transform each galaxy using a suite of N-body simulations. We present results from three co-planar flybys between disk galaxies, demonstrating that flybys can both trigger strong bar formation and can spin-up dark matter halos.

Author(s): Kelly Holley-Bockelmann[1], Meagan Lang[1], Manodeep Sinha[1]
Institution(s): *1. Vanderbilt University*

401.04 – Solving the Mystery of the Fermi Bubbles?

The Fermi Bubbles are large structures that stretch symmetrically between galactic latitudes of -55 degrees and +55 degress and between galactic longitudes of -45 degrees and +45 degrees. For almost a decade they have been under the intense scrutiny of the Fermi-Large Area Telescope, a gamma-ray detector in orbit about the earth. The Bubbles remain mysterious: Are the gamma-rays – with energies up to a few hundred GeV – produced by hadrons or do they come from Inverse Compton scattering of galactic electrons with the low energy interstellar radiation field? Why are the edges of the bubbles only 3 degree wide? How old are the bubbles.
For some time we have been considering a non-Newtonian Cosinusoidal potential U=-G M Cos[ko r]/r, and its complement, a non-Coulombic electric potential U=Q Exp[-ko r]. In both cases, ko =2 pi/400 pc. In this talk we present evidence that our putative potentials acting in concert can help answer the mysteries of the Bubbles.

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