American Astronomical Society – Division on Dynamical Astronomy
Abstract Schedule

Monday, 7 May, 2012

01 Exoplanets **Mt. Hood, 7:50AM - 11:40AM**

01.01 INVITED: Dynamical Evolution of Multiple-planet Systems

- Soko Matsumura, *University of Maryland.*

Currently, there are more than 100 confirmed multiple-planet systems. Moreover, a recent study by Kepler has identified 361 multiple-planet candidate systems. Investigating these systems would give us an important clue in understanding formation and evolution of planetary systems. In such multiple-planet systems, secular interactions among planets could play a significant role in determining the orbital evolution and/or the fate of planetary systems. In this talk, I'll focus on two such examples --- orbital evolution of multiple-planet systems with a close-in planet, and orbital stability of terrestrial planets in the presence of multiple Jupiter-like planets. In the former case, tidal interactions between the inner planet and the central star could influence the orbital evolution of the other planets. While in the latter, the orbital stability region of terrestrial planets could be significantly different from what we expect from the current observations, if we take account of the dynamical instability of Jupiter-like planets.

01.02: Stability of Multiple Planet Systems

- Alice C. Quillen, *University of Rochester.*

Three-body resonance strengths are computed for a co-planar and low eccentricity multiple planet system. A resonance overlap criterion is derived for the closely and uniformly spaced, equal mass system with three-body resonances overlapping when interplanetary separation is less than an order unity factor times the planet mass to the one quarter power. We find that three-body resonances are sufficiently dense to account for wander in semi-major axis seen in numerical integrations of closely spaced systems and they are likely the cause of instability of these systems.

01.03: Architecture and Dynamics of Kepler's Multi-transiting Planetary Systems

- Daniel C. Fabrycky[1], Kepler Science Team

  [1]*University of California, Santa Cruz.*

Having discovered almost 900 planet candidates in over 360 multiple-planet systems, Kepler has made transits a powerful method for studying the architecture and dynamics of planetary systems. Pairs of planets in this sample are typically not in orbital resonances. However, pairs with orbital period ratios within a few percent of a first-order resonance (e.g. 2:1, 3:2) prefer orbital spacings just wide of the resonance and avoid spacings just narrow of the resonance, requiring a dynamical mechanism. Several systems likely do show dynamical resonance behavior: some are engaged in very tight resonances (6:5, 9:7), and others have several planets in chains of first-order resonances. Finally, we discuss the statistics of mutual inclinations based on transit duration ratios. We infer that the inner planets of pairs tend to have a smaller impact parameter than their outer companions, suggesting these planetary systems are typically coplanar to within a few degrees. Funding for this mission is provided by NASA's Science Mission Directorate. D. F. acknowledges support from NASA through Hubble Fellowship grant #HF-51272.01-A.

01.04: Mean Motion Resonances Among Kepler Planets

- Konstantin Batygin[1], A. Morbidelli[2]

  [1]*California Institute of Technology,* [2]*Department Cassiopee, Observatoire de la Cote d'Azur, France.*

A considerable fraction of multi-planet systems discovered by the $Kepler$ mission reside in mild proximity to first-order mean motion resonances. However, the relative remoteness of such systems from nominal resonant period ratios (e.g. 2:1, 3:2, 4:3) has been interpreted as evidence for lack of resonant interactions. Here we show that a slow divergence away from exact commensurability is a natural outcome of dissipative evolution and demonstrate that libration of critical angles can be maintained tens of percent away from nominal resonance. We construct an analytical theory for the long-term dynamical evolution of dissipated resonant planetary pairs and confirm our calculations numerically. Collectively, our results suggest that a significant fraction of the near-commensurate extrasolar planets are in fact resonant and have undergone significant dissipative evolution.

01.05: Propagation of Coupled Changes in Orbital e and a via Secular Perturbations

- Richard Greenberg[1], C. Van Laerhoven[1], R. Barnes[2]

  [1]*University of Arizona,* [2]*University of Washington.*

As extrasolar planets began to be discovered, models of the histories of close-in orbits often invoked eccentricity damping or semi-major axis migration as if they occurred independently. In fact, the strong coupling of variations in *e* and *a*, e.g. if driven by tides, can significantly affect the evolution of a close-in planet, as shown by Jackson et al. (*e.g. ApJ* 678, 1396, 2008) for single-planet systems. In multi-planet systems, *e*-damping of one or more individual planets can be readily incorporated into the linear equations of classical secular theory to model the effect on all the planets of the system as angular momentum is exchanged. A greater challenge is to incorporate tidal changes in *a* as well as *e* into the secular theory. Such a theory was developed by Wu and Goldreich (*ApJ* 564, 1024, 2002), but an implicit assumption of their analysis was that it only applies if a single eigenmode has non-zero amplitude. In other words, the result can only be applied to a system that has already reached a "quasi-fixed-point" solution, i.e. after most of the system's tidal evolution has already taken place. Moreover, for some systems, if the longest-lived modes damp on near-equal timescales, there may not even be such quasi-fixed-points. What makes inclusion of changes in a relatively difficult is that, while changes in the eccentricity of a single planet just change the amplitude and phase of the eigenmodes, changes in a affect the eigenfrequencies and eigenvectors themselves. Generalized formulae that address this more general problem have been derived (Greenberg & Van Laerhoven, *ApJ* 733, id 8, 2011), and may be applied to interesting recently discovered systems.

01.06: Secular Dynamics of the Kepler-11 System

- Christa L. Van Laerhoven[1], R. Greenberg[1], R. Barnes[2]
  [1]University of Arizona, [2]University of Washington.

The secular dynamics of a multi-planet system can provide substantial insights into how dynamically coupled the planets are, how close they are to fully packed, how much the eccentricities vary, and the signatures of past eccentricity damping. Because secular interactions cause variations in eccentricities e and arguments of pericenter ϖ, the state of a system can be more meaningfully characterized by the amplitudes of the eigenmodes given by classical secular theory. For the six-planet Kepler-11 system, the theory shows that the inner planets are well coupled while, depending on its (currently unknown) mass, the outermost planet (g) may be completely decoupled or may yield a forced eccentricity on the inner planets. Eccentricity damping of any one planet damps all the eigenmodes of the system, each at its own damping rate. Even if significant damping has occurred, several of the six eigenmodes may still be strong. For Kepler-11, whether the damping is applied to the inner planet (b) or to the second planet (c) the eigenmodes are damped at approximately the same relative rates. Thus, one would be unable to differentiate between past effects of damping of these two planets. Under such damping of the inner planets, the eccentricity of the 5th planet (f) would die away long before that of the 3rd and 4th planets (d and e). Also, the stability of the system is more sensitive to the magnitude of some eigenmodes than others, which may provide insight into empirical rules that describe limits of stability. Similar implications for other multi-planet systems will also be discussed.

01.07: On the Orbit of the Circumbinary Planet Kepler-16b

- Man Hoi Lee[1], C. K. Leung[1]
  [1]The University of Hong Kong, Hong Kong.

The orbit of the circumbinary planet Kepler-16b is significantly non-Keplerian because of the large secondary-to-primary mass ratio (0.29) and orbital eccentricity (0.15) of the binary, as well as the proximity of the planet to the binary (orbital period ratio ~ 5.6). We present an analytic theory which models the motion of the planet (treated as a test particle) by the superposition of the circular motion of a guiding center, the forced oscillations due to the non-axisymmetric components of the binary's potential, the epicyclic motion, and the vertical motion. In this analytic theory, the periapse and ascending node of the planet precess at nearly equal rates in opposite directions, and the largest forced oscillation term corresponds to a forced eccentricity of 0.035. The nodal precession period (42 years) found in direct numerical orbit integration is in excellent agreement with the analytic theory, while the periapse precession period (49 years) and forced eccentricity (0.038) are slightly larger than the analytic values. The comparison with direct numerical orbit integration also shows that the planet's orbit has a nonzero epicyclic (or free) eccentricity of 0.027. This work is supported in part by Hong Kong RGC grant HKU 7034/09P.

01.08: On the Dynamical State of the HD 82943 Planetary System

- Xianyu Tan[1], M. H. Lee[1], A. W. Howard[2], G. W. Marcy[2], J. A. Johnson[3], J. T. Wright[4]
  [1]The University of Hong Kong, Hong Kong, [2]University of California at Berkeley, [3]California Institute of Technology, [4]Pennsylvania State University.

We present new results from an analysis of radial velocity data of the HD 82943 planetary system based on 10 years of measurements obtained with the Keck telescope. Previous study has shown that the HD 82943 system has two planets that are likely in 2:1 mean-motion resonance (MMR), with the orbital periods about 220 and 440 days (Lee et al. 2006). However, alternative fits that are qualitatively different have also been suggested, with the two planets in 1:1 resonance or the addition of a third planet possibly in a Laplace 4:2:1 resonance with the other two (Gozdziewski & Konacki 2006; Beague et al. 2008). Here we use the chi-square minimization method combined with parameter grid search to investigate the orbital parameters and dynamical states of the qualitatively different types of fits. Our results tend to support the 2:1 MMR configuration for this system. The fits of coplanar 2:1 MMR show a chi-square minimum at 20 degree inclination that is dynamically stable with both resonant angles librating around 0 degree. The fits of 1:1 resonance and 3-planet Laplace resonance are ruled out according to chi-square statistic and dynamical instability. This work is supported in part by Hong Kong RGC grant HKU 7034/09P.

01.09: Probability Of Capture For The 3:1 Mean-motion Resonance

- Ka Ho Chan[1], M. H. Lee[1]
  [1]The University of Hong Kong, Hong Kong.

Mean-motion resonances are frequently observed in extrasolar planetary systems. It is generally believed that the resonances result from the convergent migration of planets. The much larger number of systems near the 2:1 resonance compared to 3:1 in both the radial velocity and Kepler data may be due to a difference in the capture behaviors of 2:1 and 3:1 resonances. To study the capture probability of 3:1 resonance, we

use numerical three-body integrations with forced migration to examine how the probability depends on migration rate, planetary masses, and initial orbital eccentricities. We first confirm our numerical results with analytic theory in the adiabatic limit (Borderies & Golderich 1986) and numerical results of Hamiltonian model beyond this limit (Mustill & Wyatt 2010) for both the interior and exterior resonances in the circular restricted three-body problem. We then extend our numerical exploration of the restricted three-body problem to non-zero planet eccentricity in the adiabatic limit. The capture probability decreases with increasing planet eccentricity at small test particle eccentricity but does not depend strongly on the planet eccentricity at higher test particle eccentricity. Finally, we extend beyond the restricted problem to different planetary mass ratio m_2/m_1. In the cases where both planets are initially on circular orbits, we find that the critical migration rate for certain capture agrees with that of Quillen (2006) in the limit that one of the bodies is a test particle but that it does not change monotonically with m_2/m_1 and peaks at $m_2/m_1 = 1$. In the adiabatic regime, the capture probability for comparable masses ($m_2 \sim m_1$) shows oscillatory behaviors as a function of eccentricities, which is significantly different from the test particle limits. This work is supported in part by Hong Kong RGC grant HKU 7034/09P.

02 Planetary Formation Mt. Hood, 1:40PM - 4:00PM

02.01: Tackling Some Issues in Planet Formation - From Mars's Size to a Fast Formation of Neptune

- Harold F. Levison, *Southwest Research Institute.*

The standard model of planet formation has difficulties explaining some of the features observed in our Solar System. Of particular note, it predicts that Mars should be as massive as the Earth. In addition, it has difficulty in building the cores of the giant planets before the nebula disappeared. Here, I will argue that current models of planet formation are missing two important processes - planetesimal-driven migration and collisional grinding. I will present new simulations that include these processes. Preliminary results suggest a heretofore unknown and radical mechanism for building the outer planets.

02.02: Iceless Icy Moons: Is the Nice Model In Trouble?

- Henry C. (Luke) Dones[1], H. F. Levison[1]
  [1]*Southwest Research Institute.*

Nimmo and Korycansky (2012; henceforth NK12) stated that if the outer Solar System underwent a Late Heavy Bombardment (LHB) in the Nice model, the mass striking the icy satellites at speeds up to tens of km/s would have vaporized so much ice that moons such as Mimas, Enceladus, and Miranda would have been devolatilized. NK12's possible explanations of this apparent discrepancy with observations include (1) the mass influx was a factor of 10 less than that in the Nice model; (2) the mass distribution of the impactors was top-heavy, so that luck might have saved some of the moons from suffering large, vapor-removing impacts; or (3) the inner moons formed after the LHB. NK12 calculated the mass influx onto the satellites from the lunar impact rate estimated by Gomes et al. (2005) and scaling factors calculated by Zahnle et al. (1998, 2003; also see Barr and Canup 2010). Production of vapor in hypervelocity impacts is calculated from Kraus et al. (2011). Our preliminary results show that there is about an order-of-magnitude uncertainty in the mass striking the satellites during the LHB, with NK12's estimate at the upper end of the range. We will discuss how the mass influx depends on the velocity and mass distributions of the impactors. The Nice model lives. We thank the NASA Lunar Science Institute (http://lunarscience.nasa.gov/) for support. Barr, A.C., Canup, R.M., Nature Geoscience 3, 164-167 (2010). Gomes, R., Levison, H.F., Tsiganis, K., Morbidelli, A., Nature 435, 466-469 (2005). Kraus, R.G., Senft, L.E., Stewart, S.T., Icarus 214, 724-738 (2011). Nimmo, F., Korycansky, D.G., Icarus, in press, http://www.sciencedirect.com/science/article/pii/S0019103512000310 (2012). Zahnle, K., Dones, L., Levison, H.F., Icarus 136, 202-222 (1998). Zahnle, K., Schenk, P., Levison, H.F., Dones, L., Icarus 163, 263-289 (2003).

02.03: Accretion of Rocky Planets By Hot Jupiters

- Jake Ketchum[1], F. Adams[1], A. Bloch[2]
  [1]*University of Michigan Physics,* [2]*University of Michigan Mathematics.*

The observed population of Hot Jupiters displays a stunning variety of physical properties, including a wide range of densities and core sizes for a given planetary mass. Motivated by the observational sample, this work studies the accretion of rocky planets by Hot Jupiters, after the Jovian planets have finished their principal migration epoch and become parked in ~4 day orbits. In this scenario, rocky planets form later and then migrate inward due to torques from the remaining circumstellar disk, which also damps the orbital eccentricity. This mechanism thus represents one possible channel for increasing the core masses and metallicities of Hot Jupiters. This work determines probabilities for the possible end states for the rocky planet: collisions with the Jovian planets, accretion onto the star, ejection from the system, and long-term survival of both planet. These probabilities depend on the mass of the Jovian planet and its starting orbital eccentricity, as well as the eccentricity damping rate for the rocky planet. Since these systems are highly chaotic, a large ensemble (N ~ 1000) of simulations with effectively equivalent starting conditions is required. Planetary collisions are common when the eccentricity damping rate is sufficiently low, but are rare otherwise. For systems that experience planetary collisions, this work determines the distributions of impact velocities -- both speeds and impact parameters -- for the collisions. These velocity distributions help determine the consequences of the impacts, e.g.,where energy and heavy elements are deposited within the giant planets. This work was supported by NSF grant DMS-0806756 from the Division of Applied Mathematics, NASA grant NNX11AK87G, and NSF grant DMS-0907949.

02.04: Constraining the Dynamical History of Fomalhaut Using High-Resolution ALMA Observations

- Aaron C. Boley[1], M. J. Payne[1], S. Corder[2], W. Dent[3], E. B. Ford[1], M. Shabram[1]
  [1]University of Florida, [2]North American ALMA Science Center, [3]ALMA, Chile.

The dynamical evolution of planetary systems leaves fossil relics in the morphologies of debris disks observed today. Optical images trace micron-sized grains, which are strongly affected by stellar radiation and need not coincide with their parent body population. Observations of mm-size grains accurately trace parent bodies, but previous images lack the resolution and sensitivity needed to characterize their morphology. Here we present ALMA 350 GHz observations of the Fomalhaut debris ring. These observations demonstrate that the parent body population is 13-19 AU wide with a sharp inner and outer boundary. We discuss three possible origins for the ring, and suggest that debris confined by shepherd planets is the most consistent with the ring's morphology.

02.05: Shepherd Planets

- Matthew J. Payne[1], A. C. Boley[1], S. Corder[2], B. Dent[3], E. Ford[1], M. Shabram[1]
  [1]University of Florida, [2]NRAO, [3]NRAO, Chile.

Recent ALMA observations of the Fomalhaut system have revealed an exceptionally thin ring (FWHM ~ 16 au) at a distance ~140 au from the central star. The outer edge of the ring in these mm observations is as sharply truncated as the inner edge, leading to interesting questions regarding what causes such an abrupt outer edge. I discuss the dynamical implications of these observations, and present new models for the system in which 2 low mass 'shepherd planets' are responsible for the sculpting of this ring.

02.06: Orbital Dynamics and Habitability I: Triggering a Runaway Greenhouse via Tidal Heating

- Rory Barnes[1], K. Mullins[1], C. Goldblatt[2], V. S. Meadows[1], J. F. Kasting[3], R. Heller[4]
  [1]University of Washington, [2]University of Victoria, Canada, [3]Penn State, [4]Leibniz Institute for Astrophysics Potsdam, Germany.

The inner edge of the habitable zone is often defined by the tightest orbit which does not initiate a moist or runaway greenhouse. Previously it was believed that only stellar radiation could trigger these phenomena for a long enough duration to desiccate a planet and preclude habitability. We show that for some planets orbiting low-mass stars (<0.3 solar masses), tidal heating can reach levels that induce a runaway greenhouse. We call these planets "Tidal Venuses." As tides circularize the orbit and drive the obliquity to 0 or PI, the heating level drops, but tidal heating can persist long enough to remove all of a planet's water. Therefore, a planet may be discovered in the habitable zone with very low eccentricity (and hence without enough tidal heat to drive a runaway greenhouse), and yet be uninhabitable due to a previous epoch of extreme tidal heating. The range of possible tidal and radiative heating predicts a diversity of planets in and around the habitable zone of low-mass stars. In multi-planet systems, interactions with other companions may maintain non-zero eccentricities and obliquities, increasing the threat of catastrophic tidal heating. As terrestrial planets are discovered around low luminosity primaries, careful consideration of current and past tidal heating will be essential for estimating their likelihoods to be inhabited.

03 Brouwer Award Lecture	**Mt. Hood, 4:00PM - 5:00PM**

03.01 INVITED: Manifold-driven Spirals in Barred Galaxies

- **-** E. Athanassoulas, *LAM/OAMP, France.*

I will present and discuss the manifold (or manifold flux-tube) theory, which can explain the formation and properties of both spirals and inner and outer rings in barred galaxies using a common framework. Its building blocks are the invariant manifolds associated to the saddle unstable Lagrangian points of the bar. It explains why the vast majority of spirals in barred galaxies are two armed and trailing and what it takes for higher multiplicity arms to form. The shapes of spirals and of rings that this theory predicts are in agreement with observations. It also predicts that stronger non-axisymmetric forcings -- as measured at and somewhat beyond corotation -- will drive more open spirals. I will show examples of manifold-driven spirals from my simulations and will extend this theory to other applications than barred galaxies.

Tuesday, 8 May, 2012

04 Rings	**Mt. Hood, 8:00AM - 12:00PM**

04.01 INVITED: Dynamics of Dusty Rings

- Matthew M. Hedman, *Cornell University.*

The ring systems surrounding Jupiter, Saturn, Uranus and Neptune all contain components composed primarily of particles less than 100 microns across. These "dusty" ring features provide natural laboratories for investigating the dynamics of small particles in various environments. This talk will describe the results of recent examinations of dusty ring systems, focusing in particular on data from the highly productive Cassini Mission to Saturn. This mission has revealed many of the diverse processes that generate, transport and destroy small

particles in various environments. Individual dust particle have relatively short lifetimes in planetary rings, as small grains can be destroyed by processes like sputtering on time scales less than 1000 years. Thus the visible dust in planetary rings must be continuously re-supplied by larger source bodies. The density and spatial distribution of dusty material can therefore constrain the sources and sinks of small particles in different environments. The small size of the particles in these dusty rings also makes them particularly sensitive to non-gravitational forces. Indeed, several structures in Saturn's dusty rings exhibit periodicities that appear to be tied to asymmetries in Saturn's rotating magnetosphere, while other dusty rings show patterns in their brightness or radial structure that can be attributed to solar radiation pressure. These structures and patterns can therefore clarify how electromagnetic and radiation forces influence the spatial distribution of dusty material in various contexts. Finally, in some of the denser dusty rings (like Saturn's F ring) there is evidence for the agglomeration of dust particles. This information should aid in efforts to understand the production, growth, transport and destruction of grains in other astrophysical systems.

04.02: WISE Constraints on the Particle Properties in Saturn's Phoebe Ring

- Douglas P. Hamilton[1], A. J. Verbiscer[2], M. F. Skrutskie[2]
  [1]University of Maryland, [2]University of Virginia.

Saturn's diffuse outer Phoebe Ring is an immense disk-like structure oriented edge-on as viewed from Earth; it is 30 million km (500 Saturn ra dii) wide and 2.5 million km (40 Saturn radii) thick. The ring's particles are thought to originate primarily from the planet's dark irregular satellite Phoebe (mean radius 107km). The ring was discovered by Spitzer 24-micron imaging (Verbiscer et al., Nature 2009) and recently recovered by WISE (Skrutskie et al., DPS 2011) at 22 microns. The WISE images, which show the full extent of the ring for the first time, nicely complement the more sensitive but spatially-limited Spitzer data. Usually, ring particle populations can be determined observationally from spectral and phase angle information, but as observations of the Phoebe ring are extremely limited, we instead rely on dynamical arguments. Small particles in the Phoebe ring are expected to be driven to eccentricities in excess of Phoebe's e=0.16 by radiation pressure over 30-year timescales. Over million-year timescales, the dust distribution migrates inward via Poynting-Robertson drag, and most of the material finds its way onto the dark side of Iapetus. We model these processes numerically and build up synthetic ring profiles, making various assumptions about the unknown particle size distribution. We produce radial intensity profiles which we compare to the WISE data as well as vertical profiles which are most constrained by Spitzer. Our procedure is more robust than the onion-peeling technique used by ring scientists because it does not require the assumption of circular orbits. We find that the WISE data cannot be fit by a simple power law particle size distribution as is commonly assumed for rings. Instead, we show that the majority of the flux in the outer parts of the ring is be due to a significant excess of particles with sizes larger than several centimeters.

04.03: Chaos at Uranus Spreads Dust Across the Regular Satellites

- Dan Tamayo[1], J. A. Burns[1], P. D. Nicholson[1], D. P. Hamilton[2]
  [1]Cornell University, [2]University of Maryland.

The short collision timescales between the Uranian irregular satellites argue for the past generation of vast quantities of dust at the outer reaches of Uranus' Hill sphere (Bottke et al. 2010). Uranus' extreme obliquity (98 degrees) renders the orbits of large objects unstable to eccentricity perturbations in the radial range $a \approx 60 - 75$ Rp. (Tremaine et al. 2009). We study the effect on dust by investigating how the instability is modified by radiation pressure. We find that dust particles generated at the orbits of the irregular satellites move inward as radiation forces cause their orbits to decay (Burns et al. 1979). When they reach the unstable region, grain orbits undergo chaotic large-amplitude eccentricity oscillations that bring their pericenters inside the orbits of the regular satellites. We argue that the impact probabilities and expected spatial distribution across the satellite surfaces might explain the observed hemispherical color asymmetries common to the outer four regular satellites.

04.04: LAGEOS Satellite Drag: the Eclipse Season Mystery Remains

- Victor J. Slabinski, *U.S. Naval Observatory.*

Thermal thrust (Yarkovsky) forces explain most of the observed drag on LAGEOS satellites. The large drag variation observed during eclipse seasons depends in part on the velocity direction during Earth eclipse relative to the satellite spin vector. Scharroo et al.(1991, JGR) demonstrated that a 0.02 difference in solar reflectivity between LAGEOS hemispheres could explain the LAGEOS 1 variation. LAGEOS 2 seems to require a similar difference. The cause of such a large reflectivity difference across the spin plane is unknown. Thermal thrust analyses have not previously accounted for the differential solar heating of the two hemispheres resulting from the reflectivity difference. The darker hemisphere absorbs more solar radiation and becomes warmer than the other, thereby emitting more blackbody radiation along its end of the spin axis. The increase in the blackbody radiation reaction force on the darker hemisphere partially compensates for the reduced force from the reduced reflection of solar radiation by that hemisphere. To obtain the observed force difference between hemispheres thus requires a larger reflectivity difference than in the simple Scharroo model, which heightens the reflectivity mystery. We propose an alternate hypothesis of uniform solar reflectivity, but with the aluminum bolts which hold the cube corner reflector assemblies in place screwed in tighter on one hemisphere. This results in a different heat flow between the retainer ring assemblies and the spacecraft interior in each hemisphere, resulting in an asymmetry in the blackbody radiation force.

04.05: A Propeller in the B-ring

- Joseph N. Spitale[1], M. Tiscareno[2]
  [1]*Planetary Science Institute,* [2]*Cornell University.*

In 2009 July, close to Saturn equinox, an isolated shadow-casting object was imaged in Saturn's B-ring at an orbital radius of about 116910 km. Spitale and Porco (2010, AJ) interpreted it as an embedded satellite, whose diameter, inferred by the length of the shadow, would have been ~300 m. Although the object does not appear in any other images, which is not surprising since that radius/co-rotating longitude was only imaged once during the equinox period, it was assigned a provisional designation of S/2009 S1 by the IAU. However, if there is indeed a 300-m diameter body orbiting in the middle of the B-ring, then why does the body not seem to be perturbing the ring at all? Why was no propeller-shaped structure (e.g., Tiscareno et al. 2006, Nature) seen surrounding the object, as the simulations of Michikoshi and Kokubo (2011, ApJL) indicated it should? The answer may be that the ring is indeed perturbed and the bright feature at the base of the shadow is in fact the propeller, with the body itself not resolved. That hypothesis is further supported by an analysis of the shadow that implies that the object casting the shadow is roughly spherical (and therefore 300 m wide), much smaller than the 2-km-wide projected point-spread, while the bright feature at the base of the shadow is larger than the point-spread, and is at least 10 times wider than the height of the shadow caster. Moreover, the bright feature is slightly canted in a direction consistent with Keplerian shear. Based on the assumption that the bright feature is the only propeller to have been observed in the B-ring to date, we will discuss what can be learned by comparing B-ring and A-ring propellers, as well as the origin, evolution and fate of the observed body.

04.06: The Edge of the B Ring, Part II

- Philip D. Nicholson[1], R. G. French[2], M. M. Hedman[1]
  [1]*Cornell University,* [2]*Wellesley College.*

In 2011 we presented preliminary results from an investigation of all available occultation data for the outer edge of Saturn's B Ring, believed to be controlled by the 2:1 Inner Lindblad resonance with the satellite Mimas (Goldreich & Tremaine 1978, Porco etal. 1984). Our dataset includes 13 Voyager, Earth-based and HST occultations, as well as 138 radio and stellar occultation measurements acquired by the Cassini RSS, UVIS and VIMS instruments between May 2005 and Sept 2010. Our best-fitting model includes five distinct perturbations and 17 free parameters. In agreement with past work (Spitale & Porco 2010 [SP10]), we find that the radial perturbations of the edge are dominated by the m=2 signature associated with the ILR, but that the resonant argument circulates relative to Mimas with a period of 5.4 yrs, resulting in large variations in their amplitude and phase. Superimposed on this variable m=2 distortion is a slowly-precessing m=1 component with an amplitude of 20 km and at least three more rapidly-rotating components with m=3, 4 and 5, and amplitudes of 13, 6 and 5 km, respectively. The pattern speeds of these nonresonant perturbations are consistent with those predicted for self-excited "normal modes" generated within the outermost 150 km of the B Ring, as first noted by SP10. However, comparison of a homogeneous series of Cassini stellar occultation profiles from 2008 shows that low-m perturbations extend much further into the B Ring. Between 200 and 500 km from the outer edge we see a strong m=1 pattern which resembles a trailing spiral with a radial wavelength of ~120 km. Between 500 and 800 km from the edge, the pattern appears to switch to an m=1 leading spiral with a similar wavelength. The inner edge of this disturbed region may correspond to the Mimas 4:2 Inner Vertical resonance.

04.07: The Eccentricity Of Mimas And The Cassini Division: A Common History

- Benoit Noyelles[1], S. Charnoz[2], V. Lainey[3], K. Baillié[2]
  [1]*University of Namur, Belgium,* [2]*Laboratoire AIM, Université Paris Diderot/CEA/CNRS, France,* [3]*IMCCE / Paris Observatory, France.*

Astrometric measurements reveal the possibility that the saturnian satellite Mimas could be evolving inward instead of outward (Lainey et al. 2012), as usually thought. Based on this assumption, we studied the behavior of the satellites and the rings over 20 Myr. A numerical integration of the equations of the satellites shows that Mimas has crossed several resonances with Enceladus in the past. Moreover, a recent resonance with Tethys explains its current eccentricity (2e-2). An implementation of Mimas' dynamics in the hydrodynamical code Hydrorings (Charnoz et al. 2010, 2011) shows that we can open the Cassini Division this way, with the right width. We also highlight the mechanism of resonance leaking, able to create ringlets. We show in particular how the recent resonance with Tethys creates the Huygens ringlet. Numerical simulations were made on the local computing ressources (Cluster URBM-SYSDYN) at the University of Namur. This work is supported by EMERGENCE-UPMC grant (contract number: EME0911).

04.08: The Morphology of Saturn's F Ring

- Carl D. Murray[1], N. J. Cooper[1], N. O. Attree[1], G. A. Williams[1]
  [1]*Queen Mary, University Of London, United Kingdom.*

The unusual nature of Saturn's F ring can be understood by considering the combined effects of gravity and collisional encounters. Gravitational perturbations from Prometheus and Pandora orbiting on either side of the ring produce the regular, streamer-channel phenomenon and also trigger the formation of clumps in the ring. There is also evidence for a population of ~10km objects colliding with the ring at speeds of ~30m/s to produce jets of material that subsequently undergo Keplerian shear to form the spiral strands that emanate from the core. Evidence for a population of ~1km objects is also emerging; these appear to have similar orbits to the F ring core with collision speeds of ~2m/s. The unprecedented opportunity to study the evolving F ring in detail with the Cassini spacecraft has resulted in new insights into the dynamics of the system. We present a review of our current knowledge of the F ring, primarily derived from Cassini ISS images. We show that geometric fits for the orbit of the core are consistent with those derived from occultations and yet still show variation due to the effect of Prometheus. Cassini images documented the formation and evolution of several prominent jets many of which are associated with collisions between the object S/2004 S 6 and the core. We show that smaller jet-like features have also been observed and clumps produced by Prometheus have been tracked in the core and strands. Finally we discuss possible models to explain the formation and evolution of the population of F ring objects and the varying activity observed in the ring.

04.09: Global N-body Simulations of Broad Planetary Rings and Narrow Ringlets

- Joseph M. Hahn[1], J. Spitale[2]
  [1]Space Science Institute - Austin, [2]Planetary Science Institute.

A symplectic integrator is used to perform global simulations of a dense gravitating planetary ring. The integrator developed here uses the same drift-kick scheme at the Symba and Mercury integrators, but our code also uses the streamline concept to efficiently evaluate the ring's internal forces, namely gravity, pressure, and viscosity, that the ring exerts on each particle. Particle position and velocities are used to determine the ring's streamlines, and particles respond only to the forces that are exerted by streamlines, rather than individual particles. This approach eliminates the artificial gravitational scattering that would occur in a traditional N-body calculation. This is important because in a dense planetary ring, it is the ring's self-gravity that enables the gentle librations that the Cassini spacecraft sees along nearly all of the Saturnian ring-edges. The magnitude and pace of those librations are sensitive to the ring's surface density, and a comparison of simulations to Cassini measurements allows us to infer surface density at the A and B ring-edges, as well as the total mass of the observed Saturnian ringlets.

04.10: A New Method for Modeling Collisions in Debris Disks

- Erika Nesvold, *University Maryland, Baltimore County.*

We present a new method for simultaneously modeling, in 3D, the collisional and dynamical evolution of dust-generating planetesimals in a debris disk. Our method adapts an N-body integrator to the debris-disk problem by allowing every body to represent a swarm of planetesimals with a size distribution. When an encounter between two swarms is detected via a tree code, our algorithm calculates new size distributions and trajectories for the daughter swarms to statistically represent the outcomes of the swarm encounter. We demonstrate the validity of the model by comparing it with analytic solutions for the mass and velocity distributions of a collision cascade. We also demonstrate several advantages of our model compared to collisionless N-body integrators and 1D collisional models. Since our method solves for the collisional and dynamical evolution of the planetesimals simultaneously, it has the advantage of simulating the interaction between collisions and dynamical phenomena such as mean motion resonances and secular perturbations from planets. We plan to use it to study patterns induced by planets in debris disk images and the Late Heavy Bombardment in our Solar System.

05 Planetary Formation	**Mt. Hood, 1:40PM - 4:20PM**

05.01: Signatures Of A Putative Planetary Mass Solar Companion On The Orbital Distribution Of Tno's And Centaurs

- Rodney S. Gomes[1], J. S. Soares[1]
  [1]Observatorio Nacional, Brazil.

Gomes et al. 2006 (Icarus 184, 589) show that a planetary mass solar companion (PMSC) can produce orbits in an inner Oort cloud that can account for Sedna's orbit. On the other hand, one should expect that this faraway planet would also produce some peculiar orbital distribution for distant TNO's and Centaurs. A pair of interesting orbits in this respect are those of 2006 SQ372 and 2000 OO67. These objects have very large semimajor axes and perihelion between Uranus and Neptune orbits. It has been claimed that a likely source for 2006 SQ372 is the Oort cloud. Yet a PMSC has an important effect on objects at inner Oort cloud distances, say between 300 AU and 2000 AU, to make their perihelion distances to continually oscillate with a large enough amplitude to account for objects both inside and outside Neptune's orbit. This naturally produces an extra amount of TNO's with semimajor axes between 300 and 2000 AU and perihelion inside Neptune's orbit, like 2006 SQ372 and 2000 OO67. This signature should be found in present observations. To deal with this problem we construct a numerical simulator and apply it to populations of distant TNO's produced by numerical integration of planetesimals and planets according to the Nice model, either including or not a PMSC. With the results from the numerical simulator we compare the model with and without the PMSC with observations. We conclude that a PMSC is compatible with the existence of 2006 SQ372 and 2000 OO67 and, in fact, although not conclusively, we can also claim that the observations of 2006 SQ372 and 2000 OO67, compared to all other scattered objects, would be lucky events if no PMSC exists.

05.02: The Origin of Resonant Kuiper Belt Objects

- Kathryn Volk[1], R. Malhotra[1]
  [1]University of Arizona.

The orbital migration history of Neptune is important in the origin of the resonant Kuiper belt objects (KBOs). Proposed models for giant planet migration differ in terms of both the smoothness of Neptune's outward migration and Neptune's eccentricity evolution during this migration. Smooth migration of Neptune on a low eccentricity orbit is expected to yield a distribution of resonant KBOs with libration amplitudes and eccentricities that correlate with the magnitude of the migration. However, if the resonant KBOs originate via gravitational scattering from an eccentric Neptune, such correlations are not expected. Are the distributions of eccentricities and libration amplitudes of resonant KBOs distinguishable in the different migration scenarios? We report the preliminary results from a suite of numerical simulations of the different migration scenarios, and we discuss comparisons with observations.

05.03: Neptune's Wild Days: Constraints from the Classical Kuiper Belt

- Rebekah I. Dawson[1], R. A. Murray-Clay[1]
  [1]Harvard-Smithsonian CfA.

Neptune's dynamical history shaped the current orbits of Kuiper belt objects (KBOs), leaving clues to the planet's orbital evolution. In the "classical" region, a population of dynamically "hot" high-inclination KBOs overlies a flat "cold" population with distinct physical properties. Simulations of qualitatively different histories for Neptune -including smooth migration on a circular orbit or scattering by other planets to a high eccentricity - have not simultaneously produced both populations. We explore a general Kuiper belt assembly model that forms hot classical KBOs interior to Neptune and delivers them to the classical region, where the cold population forms in situ. First, we present evidence that the cold population is confined to eccentricities well below the limit dictated by long-term survival. Therefore Neptune must deliver hot KBOs into the long-term survival region without excessively exciting the eccentricities of the cold population. Imposing this constraint, we explore the parameter space of Neptune's eccentricity and eccentricity damping, migration, and apsidal precession. We rule out much of parameter space, except where Neptune is scattered to a moderately eccentric orbit (e>0.15) and subsequently migrates a distance Delta aN=1-6AU. Neptune's moderate eccentricity must either damp quickly or be accompanied by fast apsidal precession. We find that Neptune's high eccentricity alone does not generate a chaotic sea in the classical region. Chaos can result from Neptune's interactions with Uranus, exciting the cold KBOs and placing additional constraints. Next, we discuss how to interpret our constraints in the context of the full, complex dynamical history of the solar system. Finally, we consider constraints on Neptune's inclination and explore a scenario in which Neptune's orbit is inclined and the planet excites the inclinations of the hot objects before scattering them. We assess whether this scenario is consistent with the constraints on Neptune's dynamical history derived above. Supported by NSFGRFP DGE-1144152.

05.04: Simulations of Giant Planet Core Formation

- Henry Ngo[1], M. Duncan[1], H. Levison[2], E. Thommes[3]
  [1]Queen's University, Canada, [2]Southwest Research Institute, [3]University of Guelph, Canada.

To accrete their current gaseous atmospheres, the solid cores of our giant planets are expected to first grow to about 10 Earth masses. However, the source of the gas, the solar nebula, disperses on short timescales (1-10 Myr, based on typical observations of stars). Forming such massive cores in such a short time poses a considerable problem. We have performed numerical simulations of giant planet core formation in a disk of planetesimals with a modified version of SyMBA (Levison, Thommes, and Duncan, AJ, 2010; LTD10) that incorporates three distinct classes of objects: (1) large cores which can accrete mass, and (2) planetesimals which cannot accrete mass but can break up into (3) fragments. LTD10 used initial conditions where the cores started at equal mass, while the simulations in this work have used initial masses consistent with oligarchic growth. Nevertheless, we reproduce many of the results of LTD10, including the importance of core migration driven by planetesimal scattering. In addition, Levison, Duncan and Thommes have developed a new Lagrangian integrator ("LIPAD") built on top of SyMBA that allows for planetesimals to also accrete and eventually grow into cores. We present some preliminary results of LIPAD simulations of core formation from a cold planetesimal disk in the outer Solar System.

05.05: Planetesimal Capture by an Evolving Gaseous Giant Planet

- Nader Haghighipour[1], M. Podolak[2]
  [1]University of Hawaii, [2]University of Tel Aviv, Israel.

To explain the anomalously high abundance of heavy elements in the atmospheres of Jupiter, we have carried out an extensive study of the interactions of planetesimals with the gaseous envelope of a proto-giant planet. Both the core-accretion and disk-instability models suggest that at the last stage of the formation of a gas-giant, the core of this object is surrounded by an extended gaseous envelope. At this stage, while the envelope is contracting, planetesimals from the protoplanetary disk may be scattered into the protoplanet's atmosphere and deposit some or all of their materials as they interact with the gas. The interaction of a planetesimal with the gas is determined by three processes: gas-drag, heating, and the effect of the protoplanet's extended mass. While the gas-drag directly affects the dynamics of planetesimals, heating causes mass-loss and changes the surface to volume ratio of the object. The latter, in turn, affects the force of the gas-drag and the subsequent motion of the body. The effect of the extended mass of the protoplanet appears as variations in the gravitational potential of this object, which applies different forces to the planetesimal. These processes profoundly affect the final composition of the giant planet as the amount and type of the deposited materials are strongly tied to the number of planetesimals, their physical and dynamical states, and the state of the giant planet's envelope. We have simulated the interactions of 10,000 planetesimals with the envelope of a Jupiter-mass protoplanet. Simulations have been carried out for different radii and compositions of planetesimals so that all three processes occur to different degrees. We present the results of our simulations and discuss their implications for the enrichment of ices in giant planets and the probability of the capture of planetesimals as a function of their size, composition, and closest approach.

05.06: The Galaxy's Role in Destabilizing Planets within Wide Binaries

- Nathan A. Kaib[1], M. J. Duncan[1], S. N. Raymond[2]
  [1]Queen's University, Canada, [2]Université de Bordeaux, France.

Due to perturbations from passing field stars and the Milky Way's tide, the orbits of many wide (*a* > 1000 AU) binary stars are driven through very eccentric states. During these high eccentricity (low pericenter) phases, close passages between the binary members can deliver severe gravitational perturbations to planets residing around these stars. We find that this process eventually destabilizes 1/3 to 1/2 of all planetary systems resembling our own when they are embedded within a wide binary. Because of such instabilities, we expect that planetary systems within wide binaries should display an excited eccentricity distribution compared to planets orbiting singleton stars. Indeed, the known exoplanet catalog suggests this is the case. Using numerical simulations that employ a combination of planet-planet scattering as well as perturbations from distant stellar companions, we attempt to explain the eccentricities of known exoplanets within wide binaries.

05.07: Long-Term Obliquity Variations of a Moonless Earth

- Jason W. Barnes[1], J. J. Lissauer[2], J. E. Chambers[3]
  [1]University of Idaho, [2]NASA Ames Research Center, [3]Carnegie Institute of Washington.

Earth's present-day obliquity varies by +/-1.2 degrees over 100,000-year timescales. Without the Moon's gravity increasing the rotation axis precession rate, prior theory predicted that a moonless Earth's obliquity would be allowed to vary between 0 and 85 degrees -- moreso even than present-day Mars (0 - 60 degrees). We use a modified version of the symplectic orbital integrator `mercury' to numerically investigate the obliquity evolution of hypothetical moonless Earths. Contrary to the large theoretically allowed range, we find that moonless Earths more typically experience obliquity variations of just +/- ~10 degrees over Gyr timescales. Some initial conditions for the moonless Earth's rotation rate and obliquity yield slightly greater variations, but the majority have smaller variations. In particular, retrograde rotators are quite stable and should constitute 50% of the population if initial terrestrial planet rotation is isotropic. Our results have important implications for the prospects of long-term habitability of moonless planets in extrasolar systems.

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09 Poster Session **Raven's Nest, 4:20PM - 6:00PM**

09.01: The Spm4 Absolute Proper Motion Catalog: New Results And Applications

- Wm. F. Van Altena[1], T. M. Girard[1], D. I. Casetti-Dinescu[1], K. Vieira[2]
  [1]Yale University, [2]CIDA, Venezuela, Bolivarian Republic of.

The fourth installment of the Yale/San Juan Southern Proper Motion Catalog, SPM4, contains absolute proper motions, celestial coordinates, and B, V photometry for over 103 million stars and galaxies between the south celestial pole and -20° declination. The catalog is roughly complete to V = 17.5 and is based on observations taken with the Yale Southern Observatory's double astrograph at Cesco Observatory in El Leoncito, Argentina. The proper-motion precision is 2-3 mas/yr for well-measured stars; systematic uncertainties are on the order of 1 mas/yr. Using the same SPM observations, a more accurate catalog of 1.4 million proper motions was made over a 450 sq-deg contiguous area that encloses both Magellanic Clouds to derive the mean absolute proper motions of the LMC and the SMC and the most precise determination to date of the proper motion of the SMC relative to the LMC. The absolute proper motions are consistent with the Clouds' orbits being marginally bound to the Milky Way, albeit on an elongated orbit. Combining UV, optical and IR photometry from existing large-area surveys with SPM4 proper motions, we have identified young, OB-type candidates in an extensive 8000 sq-deg region that includes the LMC/SMC, the Bridge, part of the Magellanic Stream and the Leading Arm. Additionally, a proper-motion analysis has been made of a radial-velocity selected sample of red giants and supergiants in the LMC. These results help constrain the Cloud-Cloud interaction, suggesting a near collision that took place 100 to 200 Myr ago. Finally, SPM4 absolute proper motions have been cross-identified with radial velocities from the second release of the Radial Velocity Experiment (RAVE) and the resulting three-dimensional space motions of ~4400 red clump stars used to derive the kinematical properties of the thick disk, including the rotational velocity gradient, dispersions, and velocity-ellipsoid tilt angle.

09.02: Empirical Calibration of the P-Factor for Cepheid Radii Determined Using the IR Baade-Wesselink Method

- Michael D. Joner[1], C. D. Laney[1]
  [1]Brigham Young University.

We have used 41 galactic Cepheids for which parallax or cluster/association distances are available, and for which pulsation parallaxes can be calculated, to calibrate the p-factor to be used in K-band Baade-Wesselink radius calculations. Our sample includes the 10 Cepheids from Benedict et al. (2007), and three additional Cepheids with Hipparcos parallaxes derived from van Leeuwen et al. (2007). Turner and Burke (2002) list cluster distances for 33 Cepheids for which radii have been or (in a few cases) can be calculated. Revised cluster distances from Turner (2010), Turner and Majaess (2008, 2012), and Majaess and Turner (2011, 2012a, 2012b) have been used where possible. Radii have been calculated using the methods described in Laney and Stobie (1995) and converted to K-band absolute magnitudes using the methods described in van Leeuwen et al. (2007), Feast et al. (2008), and Laney and Joner (2009). The resulting pulsation parallaxes have been used to estimate the p-factor for each Cepheid. These new results stand in contradiction to those derived by Storm et al. (2011), but are in good agreement with theoretical predictions by Nardetto et al. (2009) and with interferometric estimates of the p-factor, as summarized in

Groenewegen (2007). We acknowledge the Brigham Young University College of Physical and Mathematical Sciences for continued support of research done using the facilities and personnel at the West Mountain Observatory. This support is connected with NSF/AST grant #0618209.

09.03: Kinematics and Dynamics of a High Order Mean-Motion Resonance: Consideration Of The Kepler-16 System

- Richard Greenberg[1], C. Van Laerhoven[1], D. C. Fabrycky[2], J. A. Carter[3]
  [1]University of Arizona, [2]University of California, Santa Cruz, [3]Harvard-Smithsonian Center for Astrophysics.

Forward numerical integration of the behavior of the planet orbiting the Kepler-16 binary star system, based on the best-fitting physical and orbital parameters, displays bounces in the eccentricity value from near zero up to ~0.1 with a period ~50 years. Correspondingly, the pericenter longitude displays the expected nearly discontinuous change when $e \approx 0$, but retrograde precession otherwise, just the opposite of a secular effect. An 11:2 mean-motion resonance may be crucial, although it is intrinsically weak (9^{th} order in eccentricities, assuming i=0, with a site of longitude conjunctions every 40°). In this type of resonance, the system may lock a critical argument $\varphi_j \equiv 11\lambda_2 - 2\lambda_1 - (9-j)\varpi_1 - j\varpi_2$ to a fixed value. For large enough values of e_2, the lock is stabilized by adjustments in n_2. For φ_1, variation of e_2 and ϖ_2 help stabilize the lock, but for φ_j with $j>2$, e_2 and ϖ_2 may destabilize the lock. For $j=2$, e_2 and ϖ_2 do not directly affect the stability, but the secular effect of the stellar orbit can play an important role: Most of the time φ_2 is locked to 180°, but as ϖ_2 regresses (due to the resonance), e changes due to the secular term in the controlling equation. Once e is very small, n_2 cannot change quickly enough to maintain the resonance lock. So φ_2 pops out of stability and quickly circulates through 360° to where it catches again in a resonance "potential well", while ϖ_2 has shifted by 180°. The system is now back in the stable configuration, and is maintained until e again approaches zero. This behavior, which is similar to that exhibited in the Kepler-16 integrations, can be described by a very simple set of equations. It can be interpreted by straightforward kinematic and physical considerations, which may give insight into high-order resonances observed in other contexts as well.

09.04: Orbital Dynamics and Habitability II: Obliquity Forcing and Suppression of the Ice-Albedo Feedback

- Rory Barnes[1], J. C. Armstrong[2], S. D. Domagal-Goldman[3], J. Breiner[1], V. S. Meadows[1]
  [1]University of Washington, [2]Weber State, [3]Goddard Space Flight Center.

We explore the impact of obliquity variations on planetary habitability in hypothetical systems with high mutual inclination. We restrict our study to systems consisting of a solar-mass star, an Earth-mass planet at 1 AU, and 1 or 2 giant planets. We verify that these systems are stable for 100 million years with N-body simulations. We then calculate the obliquity variations induced by the orbital architecture on the Earth-mass planets. We find that in some cases the spin axes can precess through over 100 degrees per thousand years. Next, we run energy balance models (EBM) on the terrestrial planets to assess surface temperature and ice coverage on the planets' oceans. Finally, we explore differences in the outer edge of the habitable zone for planets with rapid obliquity variations compared to fixed obliquity. We run EBM simulations for a range of values for the semi-major axis and find that planets undergoing extreme axial perturbations may be habitable at larger distances than those with static obliquity. This extension arises because the obliquity variations suppress the build-up of ice sheets at the poles, reducing the effectiveness of the ice-albedo-temperature feedback. The dynamical evolution of planetary systems may be a crucial feature in the distribution of life in the galaxy.

09.05: Outcomes And Duration Of Tidal Evolution In A Star-planet-moon System

- Takashi Sasaki, *University of Idaho.*

More than 700 extrasolar planets have been discovered. Although extrasolar moons have not yet been detected, they almost certainly exist - or at least they did exist at some point. When tides dissipate energy in a rotating planet, the planet/moon system evolves dynamically. Therefore, orbiting moons do not last forever. We formulated tidal decay lifetimes for hypothetical moons orbiting extrasolar planets, incorporating both lunar and stellar tides. Previous works neglected the effect of lunar tides on planet rotation, and are therefore applicable only to systems in which the moon's mass is much less than that of the planet (~<1%). This work, in contrast, can be applied to the relatively large moons that might be detected around newly-discovered Neptune-mass and super-Earth planets (up to 10% of the planet's mass). We apply our results to typical star-planet-moon systems. We conclude that moons are more stable when the planet/moon systems are further from the parent star, the planets are heavier, or the parent stars are lighter. Furthermore, moons are less stable when the mass of the moons increases for the large planets and decreases for the small planets.

09.06: The Photoeccentric Effect and Proto-Hot-Jupiters

- Rebekah Ilene Dawson[1], J. A. Johnson[2], T. Morton[2], R. A. Murray-Clay[1], D. C. Fabrycky[3]
  [1]Harvard-Smithsonian CfA, [2]California Institute of Technology, [3]University of California, Santa Cruz.

Hot Jupiters are an enigmatic class of planet, located so close to their host stars (< 0.1 AU) that they are unlikely to have formed in situ. Socrates et al. (2011) argued that the impulsive migration mechanisms proposed for situating these planets should produce an observable population of highly eccentric proto-hot-Jupiters that have not yet circularized, as well as moderately eccentric failed-hot-Jupiters, with periapses just beyond the influence of fast tidal circularization. Kepler has discovered hundreds of transiting Jupiters spanning a range of periods, but the faintness of the host stars precludes follow-up by radial velocity, the only technique used to date to measure eccentricities. Here we demonstrate a Bayesian method of measuring an individual planet's eccentricity solely from its transit light curve using prior knowledge of

its host star's density. We show that eccentric Jupiters are readily identified by their short ingress/egress/total transit durations ---the ``photoeccentric effect" ---even with long-cadence Kepler photometry and loosely-constrained stellar parameters. We measure the eccentricity of HD 17156 b from transit photometry and find it is good agreement with the value from radial-velocity measurements. We present initial results from our "distillation" of eccentric proto- and failed- hot-Jupiters from the Kepler sample. Supported by the National Science Foundation Graduate Research Fellowship under grant DGE-1144152.

09.07: On the Misalignment of the Directly Imaged Planet β Pictoris b with the System's Warped Inner Disk

- Rebekah Ilene Dawson[1], R. A. Murray-Clay[1], D. C. Fabrycky[2]
  [1]Harvard-Smithsonian CfA, [2]University of California, Santa Cruz.

The vertical warp in the debris disk β Pictoris_an inclined inner disk extending into a flat outer disk_has long been interpreted as the signpost of a planet on an inclined orbit. Direct images spanning 2004-2010 have revealed β Pictoris b, a planet with a mass and orbital distance consistent with this picture. However, it was recently reported that the orbit of planet b is aligned with the flat outer disk, not the inclined inner disk, and thus lacks the inclination to warp the disk. We explore three scenarios for reconciling the apparent misalignment of the directly imaged planet β Pictoris b with the warped inner disk of β Pictoris: observational uncertainty, an additional planet, and damping of planet b's inclination. We find that, at the extremes of the uncertainties, the orbit of β Pictoris b has the inclination necessary to produce the observed warp. We also find that if planet b were aligned with the flat outer disk, it would prevent another planet from creating a warp with the observed properties; therefore planet b itself must be responsible for the warp. Finally, planet b's inclination could have been damped by dynamical friction and still produce the observed disk morphology, but the feasibility of damping depends on disk properties and the presence of other planets. More precise observations of the orbit of planet b and the position angle of the outer disk will allow us to distinguish between the first and third scenarios. R.I.D. acknowledges support by NSF Graduate Research Fellowship DGE-1144152 and D.C.F. by NASA Hubble Fellowship HF-51272.01.

09.08: Interactions Between Moderate- and Long-Period Giant Planets: Scattering Experiments for Systems in Isolation and with Stellar Flybys

- Aaron C. Boley[1], M. J. Payne[1], E. B. Ford[1]
  [1]University of Florida.

The chance that a planetary system will interact with another member of its host star's nascent cluster would be greatly increased if gas giant planets form in situ on wide orbits. In this paper, we explore the outcomes of planet-planet scattering for a distribution of multiplanet systems that all have one of the planets on an initial orbit of 100 AU. The scattering experiments are run with and without stellar flybys. We convolve the outcomes with distributions for protoplanetary disk and stellar cluster sizes to generalize the results where possible. We find that the frequencies of large mutual inclinations and high eccentricities are sensitive to the number of planets in a system, but not strongly to stellar flybys. However, flybys do play a role in changing the low and moderate portions of the mutual inclination distributions, and erase dynamically cold initial conditions on average. Wide-orbit planets can be mixed throughout the planetary system, and in some cases, can potentially become hot Jupiters, which we demonstrate using scattering experiments that include a tidal damping model. If planets form on wide orbits in situ, then there will be discernible differences in the proper motion distributions of a sample of wide-orbit planets compared with a pure scattering formation mechanism. Stellar flybys can enhance the frequency of ejections in planetary systems, but auto-ionization is likely to remain the dominant source of free-floating planets.

09.09: A 5 Planet Outer Solar System Nice Model

- Konstantin Batygin[1], M. E. Brown[1], H. Betts[2]
  [1]California Institute of Technology, [2]Polytechnic School.

Over the last decade, evidence has mounted that the solar system's observed state can be favorably reproduced in the context of an instability-driven dynamical evolution model, such as the "Nice" model. Here we show that a large array of 5-planet (2 gas giants + 3 ice giants) multi-resonant initial states can lead to an adequate formation of the outer solar system, featuring an ejection of an ice giant during a phase of instability. Particularly, our simulations demonstrate that the eigenmodes which characterize the outer solar system's secular dynamics can be closely matched with a 5-planet model. Furthermore, provided that the ejection timescale of the extra planet is short, orbital excitation of a primordial cold classical Kuiper belt can also be avoided in this scenario. Thus the solar system is one of many possible outcomes of dynamical relaxation and can originate from a wide variety of initial states. This deems the construction of a unique model of solar system's early dynamical evolution impossible.

09.10: Resonance Angle Nodding Behavior for Planet Pairs Near Mean Motion Resonance

- Jake Ketchum[1], F. C. Adams[1], A. M. Bloch[1]
  [1]University of Michigan.

Motivated by the large number of extrasolar planetary systems that are near mean motion resonances, this paper explores a related type of dynamical behavior known as "nodding". Here, the resonance angle of a planetary system executes libration (oscillatory motion) for several cycles, circulates for one or more cycles, and then enters once again into libration. This type of complicated dynamics can affect our interpretation of observed planetary systems that are in or near mean motion resonance. This work shows that planetary systems in mean motion resonance can exhibit nodding behavior, and outlines the portion of parameter space where it occurs. This problem is addressed using both full numerical integrations of the planetary systems and via model equations obtained through expansions of the disturbing function. In the latter approach, we identify the relevant terms that allow for nodding. The two approaches are in agreement, and show that nodding often occurs when a small body is in an external mean motion resonance with a larger planet. As a result, this phenomena can be important for interpreting observations of transit timing variations, where the existence of smaller bodies is inferred through their effects on larger, observed transiting planets.

09.11: Constraining Planetary Migration in the Solar System using Satellite Orbits

- Matthew J. Payne[1], Y. Solanki[1], A. Boley[1], E. Ford[1]
  [1]*University of Florida.*

Recent models for the formation and evolution of the Solar System's giant planets require that Jupiter and Saturn migrate significant distances during the early phases of their growth. We show that simulations of satellite stability during this migration can provide constraints on the degree of migration as well as the relative proximity of the planets during this early evolution.

09.12: Lost in the Shadow of Jupiter: The Effects of Ring Particle Charging

- Douglas P. Hamilton[1], D. Jontof-Hutter[1]
  [1]*University of Maryland.*

Micrometeoroid impacts onto tiny moonlets embedded in Jupiter's dusty rings replenish the rings with grains of all sizes. These grains become electrically charged from interactions with the ambient plasma and solar photons, and their orbital motions are dominated by gravity and the electromagnetic force arising from Jupiter's rotating magnetic field. For even the simplest case of constant electric charge, this combination of forces causes both radial and vertical dynamical instabilities. When the gravitational and electromagnetic forces are comparable, positively-charged dust grains are driven to either crash into Jupiter or escape from the planet depending on their launch distance. Some smaller grains of either charge are vertically unstable, climbing up local magnetic field lines to collide with Jupiter. We understand the origin of both instabilities and have derived the relevant stability boundaries analytically (Jontof-Hutter and Hamilton 2012). Further dynamical instabilities arise when charges vary with time due to, for example, a dust grain's periodic transit through Jupiter's shadow which temporarily interrupts photoelectric currents. The eccentricities of large grains, which react nearly instantly to changes in the charging environment, are excited enough to explain the faint outward extension of Jupiter's Thebe ring (Hamilton and Krueger 2008). We expand our investigation by exploring the effect of Jupiter's shadow on dust grains of all sizes, both inside and outside synchronous orbit. The shadow extends the radial instability zones discussed above to both larger and smaller dust grains. The removal of larger grains is limited by the few-year orbital precession timescale. Smaller grains, which react slowly to differing charging conditions, suffer forces that are alternatively stabilizing and destabilizing if their electric potentials change sign. These grains evolve chaotically and most eventually become unstable.

09.13: The Rotation of Io Described by the Poincaré Model

- **Benoit Noyelles,** *University of Namur, Belgium.*

We here study the rotation of the satellite of Jupiter Io, in considering core-mantle coupling. This satellite is particularly interesting because it experiences strong tidal dissipation inducing a very active surface. Moreover, the flow of the fluid inside its core is reputed to be unstable. We first elaborate 10 different models of the interior of Io, considering either a Fe or a FeS core, using measured values of the gravity coefficients J2 and C22, before studying their response to the 4-degrees of freedom Poincaré-Hough model. We then study the stability of the flow of the fluid. We show that these different models have a quite small influence on the longitudinal librations and the equilibrium obliquity, with amplitude of about 30 and 8 seconds of arc respectively, because of the relatively small inertia of the core. However, sulfur in the core can pump the tilt of the fluid constituting the core. Moreover, in all our models the flow in unstable with a growth time of about 1,000 years for a Fe core and 5,000 years for a FeS one.

09.14: Revised Ephemerides of the Martian Satellites

- Robert A. Jacobson, *JPL/Caltech.*

Jacobson (2010 *AJ* **139**, 668) developed our previous ephemerides for the Martian satellites by fitting numerically integrated orbits to observations through 2007. We included the *Viking* and *Phobos 2* Doppler tracking data to provide information on the satellite *GM*s. We subsequently acquired the tracking data from three Phobos close approaches by the *Mars Express* spacecraft (Morley 2011 private comm.) and additional *Mars Express* imaging observations of Deimos through 2011 (Pasewaldt *et al.* 2012 *A&A* submitted). We also improved our numerical model by adopting the latest published Martian gravity field (Konopliv *et al.* 2011 *Icarus* **211**, 401) and including the gravitational effect of the tides raised on Mars by the Sun as well as by the satellites. Moreover, we adopted the Phobos forced libration amplitude which was observed with the *Mars Express* imaging (Willner *et al.* 2010 *Earth and Planetary Sci. Let.* **294**, 541). Our new ephemerides are based on our numerical model fit to all of satellite observations and spacecraft tracking data. Our fit determined the epoch states and *GM*s of the satellites, the Phobos gravitational harmonics J_2 and C_{22}, and the Martian tidal quality factor *Q*.

09.15: Asteroid Evolutionary Tracks

- Seth A. Jacobson[1], D. J. Scheeres[1]
  [1]*University of Colorado at Boulder.*

Rotational fission results in the formation of all classes of observed near-Earth asteroid (NEA) binaries. The NEA population is constantly evolving due to the incredible influence of the YORP effect, torque from the incident solar irradiation and thermal radiation of an asymmetric body, which can rotationally accelerate individual asteroids until centrifugal accelerations match gravitational accelerations, releasing part of the body into orbit and creating a binary asteroid system-i.e. rotational fission. This process has been theoretically predicted and modeled in detail [Scheeres 2007, Jacobson & Scheeres 2011], as well as observationally confirmed [Pravec et al. 2010]. Jacobson & Scheeres [2011] showed that spin-orbit coupling and solar gravitational perturbations could create stable binary systems after rotational fission. A competition between mutual body tides and the YORP torque determines whether the system quickly forms a synchronous system or whether the system remains asynchronous for millions of years. The binary YORP (BYORP) effect, which is an averaged, cumulative torque due to asymmetric thermal radiation acting on synchronized binary members, can contract or expand the mutual orbit. For the most common case, tides raised on the asynchronous primary also expand the system, while the BYORP torque on the synchronous secondary expands or contracts the system. A BYORP torque anti-aligned with the tidal torque drives the mutual orbit to an equilibrium that is stable in eccentricity. If the torques are aligned then the system expands, but as it does so, conservation of the action due to the expansion of the orbit adds energy into the spin state of the secondary, while the strength of tidal dissipation is decreasing rapidly with semi-major axis. At large semi-major axes, the secondary may de-synchronize creating an asynchronous binary. Lastly, planetary flybys can lead to sudden changes in the semi-major axis, which can de-synchronize the secondary creating asynchronous binary systems.

09.16: A Numerical Algorithm to find the Equilibrium of a Conservative System

- Benoit Noyelles[1], N. Delsate[1], T. Carletti[1]
  [1]*NAmur Center for Complex SYStems (NAXYS), The University of Namur, Belgium, Belgium.*

Determining the exact location of a (dynamical) equilibrium is a major task for the subsequent analysis of the system behavior in a neighborhood of such a point. This can be a tough task when the dynamics is complex especially when external forces are in action. We hereby present an algorithm, using frequency analysis, converging efficiently to this equilibrium when the system is perturbed by quasisinusoidal forcing. It consists in removing iteratively the free oscillations of the system. It has been successfully applied to the resonant rotation of Mercury and natural satellites in considering up to 4 degrees of freedom in the proper dynamics and 13 in the external forcing, i.e. a realistic orbital motion. It has also been used to study the orbital dynamics of exoplanets and ground-track resonances around Vesta. We finally provide a proof based on D'Alembert law and show that in a Hamiltonian case, the convergence of this algorithm is quadratic.

Wednesday, 9 May, 2012

06 Galaxies	**Mt. Hood, 8:00AM - 12:00PM**

06.01 INVITED: Velocity Fields and Dark Matter Halos

- Rachel Kuzio de Naray, *Royal Military College of Canada, Canada.*

Galaxies are expected to form inside cuspy Cold Dark Matter halos. Kinematic data like two-dimensional velocity fields provide constraints on observed halo properties. We examine the kinematic signatures of competing dark matter models and how they may be altered by the removal or redistribution of baryons during galaxy formation. We compare these results to observations of dark matter-dominated disk galaxies.

06.02: The Shape of the Local Stellar Velocity Ellipsoid

- Jerry Sellwood, *Rutgers University.*

The scattering of stars by giant molecular clouds in the disks of galaxies has a been studied extensively, yet there are still disagreements among the various contributors as to the expected shape of the velocity ellipsoid. In particular, some authors have argued that the expected distribution differs from that observed locally and that the star-cloud system cannot therefore be fully relaxed. I identify the source of the disagreement and show that the correct treatment implies that the expected shape of the ellipsoid is, in fact, consistent with that observed and. It remains true, however, that some other scattering source is need to account for the large dispersion of the older disk stars.

06.03: Structural Parameter Restrictions of Normal Spiral Galaxies Based on Chaotic and Ordered Orbital Behavior

- Maria de Los Angeles Perez Villegas[1], B. Pichardo[1]
  [1]*IA-UNAM, Mexico.*

The main objective of this work is the construction of a family of analytical models based on observational data from the literature. These models follow the classification scheme introduced by Hubble in 1926. The analysis is done through an orbital study (ordered and chaotic orbits), setting restrictions to dynamical and structural parameters for normal spiral galaxies (such as pattern speed and pitch angle). We applied several methods to study the orbital stellar dynamics, such as phase space diagrams and periodic orbits. Our main conclusion is that there are two limits for the pitch angle in late type spiral galaxies (Sc): the first limit is 20º for ordered behavior (periodic orbits), and the second limit 50º for chaotic behavior.

06.04: A New Dataset of Automatically Extracted Structure of Arms and Bars in Spiral Galaxies

- Wayne B. Hayes[1], D. Davis[1]
  [1]*UC, Irvine.*

We present an algorithm capable of automatically extracting quantitative structure (bars and arms) from images of spiral galaxies. We have run the algorithm on 30,000 galaxies and compared the results to human classifications generously provided pre-publication by the *Galaxy Zoo 2* team. In all available measures, our algorithm agrees with the humans about as well as they agree with each other. In addition we provide objective, quantitative measures not available in human classifications. We provide a preliminary analysis of this dataset to see how the properties of arms and bars vary as a function of basic variables such as environment, redshift, absolute magnitude, and color. We also show how structure can vary across wavebands as well as along and across individual arms and bars. Finally, we present preliminary results of a measurement of the total angular momentum present in our observed set of galaxies with an eye towards determining if there is a preferred "handedness" in the universe.

06.05: Recent results from the Spitzer Survey of Stellar Structure in Galaxies (S4G)

- Albert Bosma, *LAM/OAMP, France.*

I will present recent results from the S4G survey, which is an imaging survey of 2331 nearby galaxies using the Spitzer telescope at 3.6 and 4.5 μm. These include work on thin and thick disks, disk truncations, and the possibility of creating stellar mass maps from the Spitzer data alone.

06.06: Time-Variable Disk Photo-Evaporation Rates in Dense Star Clusters

- Henry B. Throop[1], J. Bally[2]
  [1]*PSI,* [2]*University of Colorado.*

Photo-evaporation sculpts protoplanetary disks during their earliest 1-5 Myr. Existing models of photo-evaporation have assumed that the distance between the disk an an external UV-bright star is fixed at ~0.1 pc. However, the star clusters in which these disks form are dynamic, with orbital crossing times of 0.1-0.5 Myr. The UV flux from a central star is therefore highly variable. We will present our simulations of photo-evaporation in a dynamic star cluster. We show that the UV flux received by disks varies by a factor of 10 - 1000 x during a disk's first several Myr. Most of the flux is deposited during brief, intense close-approaches to the central star. Photo-evaporation during this time readily affects a disk's final mass and architecture. Furthermore, the diversity of orbits through the cluster implies a broad diversity of final mass configurations for disks, even for disks with identical ages and initial conditions.

06.07: Fingerprints of Intermediate Mass Black Holes in Star Clusters

- Michele Trenti, *University of Cambridge, United Kingdom.*

Globular clusters seem to be the best place to search for Intermediate Mass Black Holes (IMBHs) in the local universe, but so far no definitive observational evidence for their existence has been found. I will review the stellar dynamics methods commonly used to search for IMBHs in these systems, evaluating in particular which signatures are uniquely associated to the presence of an IMBH. This will include our novel idea to use mass segregation and mass-dependent kinematics from proper motions as a tool to determine the presence of a central black hole.

06.08: The Role of Magnetic Fields in Relativistic Astrophysical Jets

- Nathaniel Hamlin[1], W. I. Newman[1]
  [1]*University of California, Los Angeles.*

We explore, analytically and by numerical simulation, the evolution of the Kelvin-Helmholtz (KH) instability in a relativistic magnetized astrophysical jet. Our results successfully reproduce numerous magnetohydrodynamic features observed in relativistic astrophysical environments. The KH instability arises from a variation in flow speed orthogonal to the flow. Many astrophysical jets are relativistic, evidenced by apparent superluminal motion, and are likely collimated by a magnetic field, according to commonly accepted models. We find convergence of our numerical results between the hydrodynamic, magnetohydrodynamic, relativistic hydrodynamic, and relativistic magnetohydrodynamic regimes. We observe complementarity between fluid flow and magnetic field behavior. The early nonlinear regime corresponds to the formation of large vortices connected by a dual filamentary structure reminiscent of the cosmic double helix in the extragalactic jet 3C 273. These vortices are disrupted by the field, followed by a complex turbulent regime, and then an approach to an equilibrium configuration consisting of flow-aligned filaments. For stronger fields, this process occurs more rapidly, and sufficiently strong fields suppress vortices entirely. The jet also widens and decelerates by an amount depending on field strength. These results are in qualitative agreement with observations of numerous jets, including NGC 5128, 3C 273, and HH 30. Relativistic flows break synchronicity between longitudinal and transverse motions, thereby destabilizing the system, and enhancing the complexity of vortex disruption and turbulent breakdown. This desynchronization also causes early numerical breakdown at high Lorentz factors, a long-standing problem. Using a uniform-flow model, we provide the first mathematical analysis showing that for sufficiently high Lorentz factors, artificial diffusion not only fails to suppress numerical instability, but introduces growing modes which destabilize the system in essentially all cases. This is analogous to double-diffusive instabilities, including convection associated with gradients of temperature and solute concentration in water.

06.09: From Massive Galactic Spiral Arms to Subtle Solar System Perturbations

- Stacy S. McGaugh, *University of Maryland.*

I show that a model previously fit to the terminal velocity curve of the Milky Way is in good accord with observed spiral structure. For example, the largest over density in the radial surface density profile inferred from the terminal velocities corresponds well with the Centaurus spiral arm. This suggests that the features in the terminal velocity curve are indeed due to corresponding features in the disk, and that these features are massive enough to affect the overall potential. This makes the most sense if the Galactic disk is nearly maximal, meaning that it is the dominant mass component within the solar circle. This contradicts many galaxy formation models in which the dark matter halo dominates, but is consistent with MOND. The acceleration at the solar radius is about 1.8a0, so strong MOND effects are not expected locally. Nevertheless, the external field the Galaxy may have subtle effects on planetary motions in MOND. I will attempt to connect what we observe at Galactic scales with what we might conjecture in the Solar System.

06.10: The Origins Program

- Henry Troop, *Yale University.*

07 Asteroids	**Mt. Hood, 2:00PM - 5:40PM**

07.01: Indeterminacy in the Stable States of 4-Grain Rubble Piles

- Daniel J. Scheeres, *University of Colorado.*

The sequence of all minimum energy configurations and evolutionary pathways to these states can be completely mapped out as a function of angular momentum for “cohesionless rubble piles” with 3 or less components, including their orbital configurations (Scheeres, Celestial Mechanics, in press). Once 4 grains are considered, however, there are some steps in the dynamical evolution of the system where the ultimate and possible outcomes are indeterminate. This is already well-known for the set of possible orbital configurations, as these have only been bounded but not completely discovered as of yet. More interesting for physical systems, this indeterminacy also extends to stable mixed contact and orbital configurations for the 4 body problem. We find that how the system dissipates energy, through impacts, tidal friction or a mix of these, can yield different final states. In this talk we explore the special case of 4 spheres with equal density and size, focusing on transition points as a function of angular momentum where multiple different stable configurations can occur.

07.02: Fission Limit And Surface Disruption Criteria For Asteroids: The Case Of Kleopatra

- Masatoshi Hirabayashi[1], D. J. Scheeres[1]
  [1]*University of Colorado at Boulder.*

Asteroid structural failure due to a rapid rotation may occur by two fundamentally different ways: by spinning so fast that surface particles are lofted off due to centripetal accelerations overcoming gravitational attractions or through fission of the body. We generalize these failure modes for real asteroid shapes. How a rubble pile asteroid will fail depends on which of these failure criterion occur first if its spin rate is increased due to the YORP effect, impacts, or planetary flybys. The spin rate at which the interior of an arbitrary uniformly rotating body will undergo tension (and conservatively be susceptible to fission) is computed by taking planar cuts through the shape model, computing the mutual gravitational attraction between the two segments, and determining the spin rate at which the centrifugal force between the two components equals the mutual gravitational attraction. The gravitational attraction computation uses an improved version of the algorithm presented in Werner et al. (2005). To determine the interior point that first undergoes tension, we consider this planar cut perpendicular to the axis of minimum moment of inertia at different cross-sections. On the other hand, we define the surface disruption as follows. For an arbitrary body uniformly rotating at a constant spin rate there are at least four synchronous orbits, which represent circular orbits with the same period as the asteroid spin rate. Surface disruption occurs when the body spins fast enough so that at least one of these synchronous orbits touches the asteroid surface. Kleopatra currently spins with a period of 5.38 hours. The spin period for surface disruption is computed to be 3.02 hours, while the spin period for the interior of the asteroid to go into tension is about 4.8 hours. Thus Kleopatra’s internal fission could occur at spin periods longer than when surface disruption occurs.

07.03: Detection of Semi-Major Axis Drifts in 55 Near-Earth Asteroids

- Carolyn Nugent[1], J. Margot[1], S. R. Chesley[2], D. Vokrouhlicky[3]
  [1]*UCLA,* [2]*Jet Propulsion Laboratory, California Institute of Technology,* [3]*Charles University, Czech Republic.*

We have identified and quantified semi-major axis drifts in 55 Near-Earth Asteroids (NEAs), after performing fits to all NEAs with 15 or more years of astrometric data. Our selection criteria include a Yarkovsky sensitivity metric that quantifies the detectability of semi-major axis drift in any given data set. In 42 cases, the observed drifts (~10^3 AU/Myr) agree well with numerical estimates of Yarkovsky drifts. In 13 cases, the drifts exceed nominal Yarkovsky predictions, which could be due to inaccuracies in our knowledge of physical properties or to modeling errors. If these high rates cannot be ruled out by further observations or improvements in modeling, they would be indicative of the presence of a non-gravitational force, such as that resulting from a loss of mass of order a kilogram per second. We define the Yarkovsky efficiency f_Y as the ratio of the change in orbital energy to incident solar radiation energy, and we find that typical Yarkovsky efficiencies are ~10^{-5}.

07.04: Effect of Small Scale Surface Topology on Near-Earth Asteroid YORP and bYORP Coefficients

- Jay W. McMahon[1], D. Scheeres[1]
  [1]*University of Colorado - Boulder.*

Several important dynamical processes for Near-Earth asteroids (NEAs) depend intrinsically on the surface topology of the asteroid. Most notably these include reflection of radiation (YORP and bYORP), thermal emission (the Yarkovsky effect), gravity, and surface accelerations. In this work, we concentrate our investigation on the variability in bYORP and YORP (b/YORP for short) coefficients of NEAs based on the high resolution shape models available for Itokawa. First, we discuss the changes in surface topology seen on Itokawa for shape models of increasing resolution. These changes are quantified in terms of variation in surface orientation and height. We then show how the b/YORP coefficients change as we look at models of increasing resolution. Note bYORP coefficients can be calculated even if the body is not part of a binary system as they only depend on the body parameters, not the binary orbit. Finally, we use the results for Itokawa to predict the possible variability in the b/YORP coefficients for other NEAs with available shape models including 1999 KW4 and 1998KY26.

07.05: Collapsing Binary Asteroids With YORP And BYORP

- Patrick A. Taylor, *Arecibo Observatory.*

A separated binary system may be collapsed to contact via the removal of angular momentum from the system until a viable tidal end state no longer exists. The thermal YORP and BYORP effects are both capable of removing angular momentum from the system, by spin-down of the components and shrinking the mutual orbit, respectively. The YORP effect, with strength of order that measured for (1862) Apollo [1], can collapse a binary system with equal-mass components in as little as tens of thousands of years (depending on the initial angular momentum), while smaller secondaries require two or more orders of magnitude longer to collapse. BYORP, with a BYORP coefficent of 0.001 [2], is less

efficient, especially for smaller secondaries. By these methods, only near-Earth binaries with large mass ratios can collapse within a dynamical lifetime, a population of which is observed by radar with a frequency comparable to separated binaries. [1] Kaasalainen et al., 2007, Nature 446, 420-422. [2] McMahon and Scheeres, 2010, Icarus 209, 494-509.

07.06: Dynamical Architecture of Multi-Component Systems

- Julia Fang[1], J. Margot[1]
  [1]*University of California, Los Angeles.*

Several multiple systems (triples and higher multiplicities) have been discovered among near-Earth asteroids, main belt asteroids, and trans-Neptunian objects. Here we focus on systems with at least three components, and we perform a detailed N-body analysis of their intricate dynamics with the goals of furthering our knowledge of their physical and orbital characteristics. This enables us to measure masses and densities, and to gain insight into formation and evolutionary processes. Plausible evolutionary paths leading to a multiple system's current orbital configuration can be simulated with dynamical models to understand the system's origin and evolution. Our models explore important evolutionary effects such as tidal evolution, radiative processes, close gravitational encounters, and solar perturbations. We examine the current and past history of several multiple systems, including near-Earth triples 2001 SN263 and 1994 CC, main belt triples Sylvia and Eugenia, and trans-Neptunian triple 1999 TC36.

07.07: Dynamics of Binary Near-Earth Asteroid System (35107) 1991 VH

- Shantanu P. Naidu[1], J. L. Margot[1], M. W. Busch[1], P. A. Taylor[2], M. C. Nolan[2], E. S. Howell[2], J. D. Giorgini[3], L. A. M. Benner[3], M. Brozovic[3], C. Magri[4]
  [1]*University of California,* [2]*Arecibo Observatory,* [3]*Jet Propulsion Laboratory, California Institute of Technology,* [4]*University of Maine.*

Near-Earth Asteroid (35107) 1991 VH was discovered to be a binary in March 1997, based on its light-curve (IAUC 6607). It made a very close approach to the Earth in August 2008 at a distance of 0.045 AU. We used this opportunity to secure an extensive radar data set with the Arecibo S-band (2380 MHz, 13 cm wavelength) planetary radar system, including range-Doppler images with spatial resolution as fine as 15 m. The images (spanning 14 days) reveal that the primary is roughly spheroidal with a radius of ~650 m. The range extent of the secondary in these images varies from less than 100 m to more than 200 m indicating that it is highly elongated. The radar data provide an excellent determination of the mutual orbit: The orbital period is ~32 hours, the eccentricity is ~0.05, and the total system mass is ~1.5e12 kg. Numerical simulations of the spin of the elongated secondary in this eccentric mutual orbit reveal a large region of chaos in the phase space, similar to that observed in Saturn's moon Hyperion (Wisdom, Peale, Mignard 1984). The chaotic region surrounds the 1:2, 1:1, 3:2 and 2:1 spin-orbit resonances, but allows for islands of stability around the 1:2 and 1:1 spin-orbit states. The secondary's echo bandwidths indicate that its spin rate indeed lies within or very close to this chaotic region. To date no acceptable fit to the sequence of secondary images has been found under the assumption of synchronous spin. Saturn's moon Hyperion is the only solar system object known so far to have a chaotic spin state (Wisdom, Peale, Mignard 1984).

07.08: The Trajectory Dynamics of Near-Earth Asteroid 101955 (1999 RQ36)

- Steven R. Chesley[1], M. C. Nolan[2], D. Farnocchia[3], A. Milani[4], J. Emery[5], D. Vokrouhlický[6], D. S. Lauretta[7], P. A. Taylor[2], L. A. M. Benner[1], J. D. Giorgini[1], M. Brozovic[1], M. W. Busch[8], J. Margot[8], E. S. Howell[2], S. P. Naidu[8], G. B. Valsecchi[9], F. Bernardi[3]
  [1]Jet Propulsion Laboratory, California Institute of Technology, [2]Arecibo Obs., [3]SpaceDys s.r.l., Italy, [4]University Pisa, Italy, [5]University of Tennessee, [6]Charles University, Czech Republic, [7]University Arizona, [8]Uniersity. California, [9]IAPS-INAF, Italy.

07.09: Resonant Flyby and Tour Design Using Heteroclinic Connections

- Rodney L. Anderson, *Jet Propulsion Laboratory/California Institute of Technology.*

Tour design has traditionally relied on the use of two-body patched conic techniques in combination with differential correction or optimization algorithms. Recently, three-body effects have increasingly been included more directly in the design and analysis problem using a variety of different methods. In previous work it was shown that ballistic, impulsive, and low-thrust trajectories follow the invariant manifolds of unstable resonant and libration point orbits as they traverse resonances and approach the desired body in the circular restricted three-body problem (CRTBP). The invariant manifolds of these resonant orbits have now been used to compute heteroclinic connections between different resonant orbits. The heteroclinic connections have then been exploited to select particular flybys that travel between desired resonances, and sequences of heteroclinic connections have been chained together to obtain nearly ballistic trajectories that traverse the sequence of resonances. Approaches to the desired moon or planet have also been shown to heuristically follow both the invariant manifolds of unstable resonant and libration orbits in the planar problem. In particular, specific unstable manifolds of selected resonant orbits can be used to compute landing trajectories or approach desired orbits around the secondary in the CRTBP. The heteroclinic connections and approach analyses provide a framework for both designing trajectories traveling on a tour and analyzing the movement of objects through these resonances. The techniques also provide a means to form geometric and visual tools for analyzing and designing these types of trajectories. The current state of this research is described here, and particular examples of trajectories are presented. These trajectories may be used directly or as inputs to algorithms that can further refine the trajectory. The output from this process lays the foundation for reaching the goal of designing complete tours by chaining heteroclinic connections of resonant orbits together in multiple systems.

07.10: Keyholes and Jabbas: The Role of Pre-Impact Close Approaches in Asteroid Deflection

- Paul Chodas, *Jet Propulsion Laboratory, California Institute of Technology.*

The basic problem of deflecting a threatening Near-Earth Object on a "direct" collision course with the Earth has a straightforward solution: we would apply a velocity change in the along-track direction, so that over time the object would move far enough ahead or behind its original position that it would miss the Earth. But the deflection strategy must also take into account the not unlikely possibility of pre-impact Earth close approaches, which can either aid or hamper deflection attempts. The potential 2036 impacting trajectory for Apophis is a good example: the trajectory makes an extremely close Earth encounter 7 years earlier, passing through a 600m-wide keyhole in the 2029 target plane. If the deflection is performed before 2029, the trajectory needs to be shifted by less than a kilometer; otherwise, the necessary shift in the impact target plane is 4 orders of magnitude larger. Keyholes have the useful effect of amplifying along-track displacements, providing deflection leverage. What are the chances that a random impacting asteroid will have a keyhole providing such large deflection leverage? We study this question statistically using a large set of simulated impactors and show that the Apophis scenario is extremely unlikely; in fact, less than 10 percent of impactors will have keyholes with leverage of only 1 order of magnitude within 25 years of impact. The study also showed the prevalence of the converse effect, produced by more distant pre-impact encounters. These close approaches produce large regions in the target plane called "jabbas", which have the undesirable property of reducing or absorbing the effect of a prior deflection. About 8 percent of the impactors had jabbas which reduced deflection effects by at least an order of magnitude. Deflection of these objects may be easier to accomplish after the asteroid has passed through the jabba encounter.

Thursday, 10 May, 2012

08 Satellites and Obliquities **Mt. Hood, 8:00AM - 11:40AM**

08.01 INVITED: Tidal Evolution of Multiple Moons around Solid Planets

- Matija Cuk, *SETI Institute.*

Tidal evolution of satellites around giant planets and resulting resonant configurations are one of the iconic problems of modern Solar System dynamics, but their lessons do not apply directly to terrestrial planets. Tidal dissipation within gas giants is weak, making it possible for satellite tides to dissipate eccentricity excited by mutual mean-motion resonances. Stronger tidal dissipation within terrestrial planets leads to faster tidal evolution, and even if the eccentricity is damped during outward evolution, inevitable resonances will always excite eccentricities and/or inclinations, eventually leading to destabilization. This was clearly demonstrated by Canup et al. (1999), who explored long-term stability of flat terrestrial multiple moon systems. My own three-dimensional integrations confirm this result, and show that even pure inclination

resonances cannot be stable. Both outward evolution and despinning of the planet reduce precession due to oblateness, causing sub-resonance overlap which enables the conversion of inclination into eccentricity. Trojan coorbitals do not excite mutual eccentricities, but are vulnerable to solar perturbations (Cuk and Gladman 2009). Despite the above considerations, dwarf planet Haumea currently has two large satellites which are likely billions of years old (Ragozzine and Brown 2009). The moons are well separated and their formation much closer to Haumea would require unrealistically dissipative Haumea (Q=0.1), apart from likely resonance capture and instability. Haumea's moons substantial eccentricity and inclination still suggest some kind of resonant excitation, and the bet-fit system is sometimes found librating around 8:3 mean motion resonance. I will show that the capture and evolution in the mutual 8:3 resonance can explain the current orbits of the satellites. This capture requires more reasonable level of tidal dissipation, but implies that the present satellites must have formed far from Haumea, close to their present orbits.

08.02: Compositions And Origins Of Outer Planet Systems: Insights From The Roche Critical Density

- Matthew S. Tiscareno[1], M. M. Hedman[1], J. A. Burns[1], J. C. Castillo-Rogez[2]
  [1]Cornell University, [2]JPL.

Obtained by inverting the familiar Roche limit equation, the Roche critical density ρ_{crit} is the minimum density of an orbiting object that, at a given distance from its planet, is able to hold itself together by self-gravity. An object whose bulk density $\rho<\rho_{crit}$ will be pulled apart (unless held together by internal strength), and its material will form a ring. Conversely, when abundant material is available for accretion, an object with $\rho>\rho_{crit}$ will accrete until its ρ has decreased to ρ_{crit}, at which point it has "filled its Roche lobe" and will stop accreting. Both Saturn and Uranus have clear boundaries between accretion-dominated regions (populated with moons) and disruption-dominated regions (populated with rings). Given the presence, in both cases, of abundant material for accretion, the value of ρ_{crit} at the boundary should be similar to the density of transient clumps. Noting that these boundary values are 1.2 g/cm^3 for Uranus but only 0.4 g/cm^3 for Saturn, we infer that the material composing Saturn's rings is likely intrinsically less dense than that composing Uranus' rings by a factor ~3. This is consistent with several observational clues. The "Portia group" of eight Uranian moons packed between 2.31 to 2.99 R_U has an overall surface density similar to that of Saturn's A ring. Thus, this region can be understood as having a character similar to the known dense ring systems, except that it is dominated by accretion rather than by disruption due to the region's low ρ_{crit}. Neptune and Jupiter have moons and rings interspersed, with moons at locations where ρ_{crit}~2 g/cm^3. Thus, these moons may be interlopers that formed farther from their planets and have since migrated inward and are held together by internal strength, or it may indicate that they are composed of denser (perhaps partly silicate) material.

08.03: Cupid is Still Doomed: Overlapping Power Laws and the Stability of the Inner Uranian Satellites

- Robert S. French[1], M. R. Showalter[1]
  [1]SETI Institute.

We have continued our exploration of the stability of the inner Uranian satellites (French & Showalter 2011, DDA abstract) using simulations based on recent observational data. We find that the moon subsets Cressida/Desdemona/Juliet and Cupid/Belinda/Perdita are unstable in isolation, crossing orbits in 10^6-10^7 years. The presence of the other inner moons reduces this time to 10^4-10^6 years. The stability of the inner moons is not changed by the presence of the five classical satellites but Perdita, a very small moon, has a surprisingly large effect on the stability of Cupid and Belinda. We extend the power law previously discovered by Duncan & Lissauer (1997, Icarus, 125, 1-12), in which the crossing time of a pair of moons can be predicted using multiple simulations with higher moon masses, to the case of two unstable moon pairs. We use this new formalism to predict the lifetimes of Cupid/Belinda and Cressida/Desdemona using a conservative density assumption, ρ=0.5 g/cm^3. The inner satellites continue to exhibit instability with crossing times of 10^5-10^7 years in this case. Such short crossing times imply the continuing, rapid evolution of the Uranian satellites.

08.04: Rotational Kinematics and Torques for Triaxial Bodies: A Simple Derivation of Precession with Synchronous Locking

- William I. Newman, *UC, Los Angeles.*

Precession of the equinoxes and of satellite orbits for axisymmetric bodies is a celebrated part of the classical and orbital mechanics literature. The theory underlying the behavior of triaxial bodies, particularly when synchronous phase locking is present, has proven to be difficult to evaluate and controversial. We perform a first-principles derivation where we incorporate triaxial geometry into the analysis using a straightforward description of the configuration. We calculate the effect of triaxiality and phase locking upon precession rates by using multiple time scales techniques. This is required to make possible the direct numerical integration of the kinematic equations of motion over solar system time scales. In so doing, we provide a simple derivation of the time-averaged gravitational potential and the associated torque that drives precession, and resolve an outstanding controversy emerging from its calculation.

08.05: Long-term Rotation State Evolution of Comet Nuclei Including the Effects of Jet Torques and Internal Dissipation

- Seth A. Jacobson[1], D. J. Scheeres[1]
  [1]University of Colorado.

Many comet nuclei have been identified or are suspected to occupy non-principal axis (complex) rotation [Belton 2005, etc.] as well as have evolving rotation rates [Belton 2011, etc.]. Active areas of the surface and jets torque the nucleus during perihelion passage, while time variable internal stresses dissipate energy in the anelastic comet interior. These competing processes determine the comet's nuclear rotation state. We developed a model for the evolution of the nuclei due to the reactive torques of a number of discrete jets located on the surface based on Neishtadt et al. [2002]. These jets are active only within a specific distance of the sun according to an empirical law determined by Marsden et al. (1973), however internal dissipation occurs as long as the body is not rotating about a principal axis. This internal dissipation is modeled according to Sharma et al. [2005] and Vokrouhlicky et al. [2009]. We average the full evolutionary equations over the rapidly changing spin angle, precession angle and true anomaly of the orbit. The averaged equations can rapidly calculate the long-term evolution of the nutation angle, cone angle and magnitude of the angular momentum vector over many perihelion passages. The averaged dynamical system is characterized by just two parameters: the first encapsulating the jet geometry and the second the coefficient of energy dissipation. Neishtadt et al. [2002] determined that there exist non-principal axis rotation fixed points, some even stable, for certain jet geometries. With the addition of internal dissipation, some of these fixed points disappear, while others remain but may change locations and classification as a function of the strength of energy dissipation at constant jet geometry. We explore this model of comet nuclei evolution to determine the rotation state of comet nuclei with changing jet geometries and constant coefficients of energy dissipation.

08.05: Dissipation and Synchronization due to Creeping Tides.

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We present a new reophysical theory of the dynamical tides of celestial bodies. It is founded on a Newtonian creep instead of the classical delayed elastic approach of the standard viscoelastic theories. All results of the theory derive from the solution of a non-homogeneous ordinary differential equation and lags appear as a natural outcome from the solution of the equation and are not external ad hoc quantities plugged in an elastic model. The lag due to the Newtonian creep is proportional to the tide frequency (as in Darwin's original theory), and is necessarily small. The amplitudes depend on the viscosity of the body and on the frequency of the tide. As a consequence, the so-called pseudo-synchronous rotation has an excess velocity roughly proportional to 6ne^2/(χ^2+1/χ^2) (χ is the tide frequency in units of a relaxation factor inversely proportional to the viscosity) instead of the exact 6ne^2 of standard theories. The dissipation is inversely proportional to (χ + 1/χ); thus, in the inviscid limit it is roughly proportional to the frequency (as in standard theories), but that behavior is inverted when the viscosity is high and the response factor much smaller than the tide frequency. When the viscosity is high, however, the creeping tide fails to reproduce the actual geometric tide and, to reconcile theory and observation, we need to assume the coexistence of a small elastic tide superposed to the creeping tide. The theory is applied to several Solar System and extrasolar bodies and the values of the relaxation factor μ (and its current correspondent Q) are derived for these bodies on the basis of currently available data.

08.07: Influence of an Inner Core on the Long-period Forced Librations of Mercury

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The planetary perturbations on Mercury's orbit lead to long-period forced librations of Mercury's mantle (see for example Dufey et al 2008, Peale et al 2009, Yseboodt et al 2010). These librations have been studied for a planet with two layers: a mantle and a liquid core. Here, we calculate how a solid inner core inside a liquid outer core influences the long-period forced libration and derive the analytical expression for the amplitudes. We use recent models about the interior structure of Mercury and make different assumptions about the flattening of the internal layers. The periods of the two free modes are between 10 and 15y and between 4 and 5y. Since the orbit is affected by many planetary periods, resonance effects could happen and the planetary librations might be amplified for some interior model. We also look for the interior model with an inner core that gives a rotation model that best fits the radar data of Margot et al (2007).

08.08: Orbit Determination in the Pluto System

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The once simple binary system of Pluto and Charon has, until now, eluded a precise description of its orbital motion. The most important component that makes this system so difficult is a consequence of its fully relaxed spin-orbit state. The surface of Pluto has a highly variable albedo that also changes with time. These albedo variations lead to a shift of the photocenter relative to the center of the body. The synchronicity of the rotation of Pluto and the orbit of Charon couples the albedo pattern to the astrometry and lead, if uncorrected, to erroneous values for the orbital elements. In this presentation we will show results based on astrometry with the Hubble Space Telescope that now span nearly 20 years. We use two-body Keplerian orbit fits to describe the motions of all satellites as a tool to understand and remove the astrometric effects of the albedo pattern. The most immediate result of this work is a demonstration that the orbit of Charon is very close to circular (1-sigma limit is 3 km out of round). We also present an analysis of the degree to which albedo effects (spatial and temporal) impact the astrometry the resulting orbit determinations. These considerations show the value and necessity of combining photometric and astrometric data to further improve the dynamical description of this system. This work is a necessary precursor to upcoming New Horizons encounter with Pluto as well as our on-going work to determine the masses of the outer satellites. This work was supported by grants from NASA Planetary Astronomy and from the Space Telescope Science Institute.

08.09: Pluto's "p4" And The Search For Additional Moons And Rings

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We report on the discovery and subsequent analysis of "P4", Pluto's fourth known moon (officially designated S/2011 (134340) 1). P4 was discovered in Hubble Space Telescope images from June and July 2011, and recovered in follow-up observations during September 2011. Numerous pre-discovery detections have now been identified in the Hubble archive, spanning 2005-2011. These detections provide a long time baseline for determining the body's orbital elements. Based on a preliminary analysis of the 2011 data, the body has an orbital period of 32.1 days, placing it at a semimajor axis near 59,000 km, between thte orbits of Nix and Hydra. It appears to fit the general trend of orbital elements in the Pluto system, with Nix near the 1:4 orbital resonance with Charon, P4 near the 1:5, and Hydra near the 1:6. All orbits are coplanar and nearly circular. This configuration suggests that the bodies formed in place rather than as captured objects. The diameter of P4 depends on the assumed geometric albedo: 14 km if its albedo ~ 0.35, comparable to that of Charon, or 40 km if it has a much darker albedo ~ 0.04, which would be more typical of other Trans-Neptunian Objects. We also report on the search for rings of Pluto. We can exclude any faint rings comparable in reflectivity to the Jovian ring, orbiting anywhere near or beyond the orbit of Charon.