39th Meeting of the AAS Division on Dynamical Astronomy
Boulder, Colorado, 28 April - 1 May 2008

All talks, except for the public lecture on Monday night, will be held in the St. Julien Hotel.
Invited talks marked with "I" will be 45 min (40 min + 5 min Q&A)
Contributed talks will be 20 min (15+5). Talks should be uploaded to the laptops provided by the meeting organizers before each session.
The Poster Session will be in SwRI's 4th floor conference room, 1050 Walnut St. around the corner from the St. Julien Hotel. Posters may be put up 8 AM - 5 PM on Monday, Tuesday, or Wednesday.

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MONDAY, 28 April 2008

The Opening Word of the DDA Chair

Monday, April 28, 2008, 8:15 am - 8:20 am

DDA Chair

William R. Ward[1]
[1]*Southwest Research Inst.*

Session 01 Stars and Galaxies

Oral, Monday, April 28, 2008, 8:20 am - 10:25 am

01.01I **Telling Tales with Tidal Tails**

Kathryn V. Johnston[1]
[1]*Columbia Univ.*

The distributions of stars in the different components of galaxies are broadly described in terms of analytic density and velocity distributions functions that are constructed to be in equilibrium with the underlying potential. In the last decade, the stellar halos of the Milky Way and Andromeda galaxies have been mapped in exquisite detail, revealing that they are actually richly substructured in phase-space due to the presence of debris from tidally disrupted satellites. These observations are qualitatively consistent with our expectations for large galaxies formed hierarchically from smaller galaxies, but are they actually telling us anything more quantifiable? In this talk I will review the origin of these substructures and discuss what they can tell us about the history and total mass distributions of these galaxies.

01.02 **Stellar Dynamical Evidence against a Cold Disk Origin for Stars in the Galactic Center**

Jorge Cuadra[1], P. J. Armitage[1], R. D. Alexander[2]
[1]*JILA, University of Colorado,* [2]*Leiden Observatory, Netherlands.*

Observations of massive stars within the central parsec of the Galaxy show that while most stars orbit within a well-defined disk, a significant fraction have large eccentricities and / or inclinations with respect to the disk plane. Here, we investigate whether this dynamically hot component could have arisen via scattering from an initially cold disk -- the expected initial condition if the stars formed from the fragmentation of an accretion disk. Using N-body methods, we evolve a variety of flat, cold, stellar systems, and study the effects of initial disk eccentricity, primordial binaries, very massive stars and intermediate mass black holes. We find, consistent with previous results, that a circular disk does not become eccentric enough unless there is a significant population of undetected 100-1000 Msun objects. However, since fragmentation of an eccentric disk can readily yield eccentric stellar orbits, the strongest constraints come from inclinations. We show that *none* of our initial conditions yield the observed large inclinations, regardless of the initial disk eccentricity or the presence of massive objects. These results imply that the orbits of the young massive stars in the Galactic Center are largely primordial, and that the stars are unlikely to have formed as a dynamically cold disk.

01.03 Redshift Asymmetry as an Indication of Dark Energy around Groups of Galaxies

Mauri J. Valtonen[1], S. Niemi[2], P. Teerikorpi[1], A. D. Chernin[3], I. Karachentsev[4], P. Heinämäki[1], P. Nurmi[1]
[1]Univ. of Turku, Finland, [2]Nordic Optical Telescope, Spain, [3]Univ. of Moscow, Russian Federation, [4]Special Astrophysical Observatory, Russian Federation.

Einstein's lambda-term or the dark energy creates regions of cool galaxy expansion flows outside the virialized group beyond the zero-gravity sphere [1]. It has been demonstrated [2] that the flows identified as expanding population around galaxy groups may show redshift asymmetries. The corresponding asymmetries are found also in observed galaxy group samples [3,4]. We use the HST observations of the environments of the Local Group of galaxies and of two other groups to demonstrate that the cool outflow regions do exist around galaxy groups on the spatial scales of a few Mpc. Then we use numerical simulations of lambda-dominated cosmological models to show that groups of galaxies indeed should possess expanding populations which reveal redshift asymmetries when viewed from outside at a reasonably close distance. Thus the observation of "anomalous redshifts" in 1970 proved highly significant in the case of groups of galaxies, and it pointed to the existence of dark energy even though it took many decades to fully understand the implications.

References: 1. Chernin et al. 2007, A&A 467,933; 2. Byrd & Valtonen 1985, ApJ 289,535; 3. Arp 1970, Nature 225, 103; 4. Sulentic 1984, ApJ 286, 442.

01.04 Reconstructing the Mass Profile of the Milky Way

Stacy S. McGaugh[1]
[1]Univ. of Maryland.

I attempt to recover the radial surface mass density profile of the Milky Way from the observed terminal velocity curve. This procedure is formally straightforward but fraught in practice. I make use of the empirical coupling between luminous and total mass observed in external galaxies as an additional constraint. The result is a Milky Way with bumps and wiggles in its inferred surface brightness profile that is reminiscent of those observed in other spiral galaxies.

01.05 Does M42 Presage the Dual Proposal?

David F. Bartlett[1]
[1]Univ. of Colorado.

Messier's drawing of the Orion Nebula shows a clear interface between nebula and void. A line extended along this front points straight towards the Milky Way. Ditto for the other well-known photodissociation region, M17, the Omega Nebula [1]. These nebulae differ in location: M17 is about 2000 pc away in the direction of the Galactic center. M42 is exactly 414 pc (Menten, Reid, Forbrich, and Brunthaler 2007) in the opposite direction. In this talk I will show how these observations support the 'Dual Proposal' which has a universal wave length of 400 pc. I also will suggest what further observations can distinguish this proposal from the standard theory.

The Dual Proposal [2] alters both the theory of electromagnetism and the theory of gravitation in complementary ways. Here the photon has a real mass and the graviton an imaginary one, both masses given by $mc^2=hc/\lambda_o$ = 10^[-25] eV, where λ_o = 400 pc. The resulting sinusoidal gravitational potential (φ = - (GM/r) Cos[k_or], $k_o=2\pi/\lambda_o$) has a unique feature: *maxima* of potential where gas can stall and create stars. Correspondingly the massive photon produces an electrostatic Yukawa potential φ= (Q/r) Exp[-k_or] and generalizes Maxwell's stress tensor by adding terms in the vector potential **A**. For scales greater than 400 pc, even weak **B**-fields can have a strong influence on the

plasma within the stream. Finally the new scale λ_o may, someday, relate gravitation to atomic physics. By equating inertial and gravitational energy densities, I find a numerical relationship: $c^4 k_o^2/2\pi G = 13.6\ eV/(137a_o)^3$, where a_o is the Bohr radius. Refs [1] Facts on File: Dictionary of Astronomy 5th ed (2006). [2]: "Analogies between electricity and gravity", Metrologia 41 (2004) S115-S124.

Session 02 The Yarkovsky and YORP Effects

Oral, Monday, April 28, 2008, 10:45 am - 12:30 pm

02.01I Analytic Theory of the YORP Effect for Near-Spherical Objects

David Nesvorny[1]
[1]*SwRI.*

The YORP effect is produced when the surface of a small object in the interplanetary space is heated by sunlight and re-radiates the absorbed energy in thermal wavelengths. The absorbed, reflected and emitted photons produce tiny torques on the small body which can change its spin rate and obliquity over planetary timescales. Previous theories of the YORP effect relied on numerical or semi-numerical evaluation of the radiation torques. Here we develop an alternative approach and calculate the YORP torques analytically. Our theory is limited to near-spherical objects. While unsuitable for a precise determination of torques on elongated and/or highly-irregular objects, the analytic theory helps to explain several general properties of the YORP torques that were identified in previous numerical works. We discuss applications of the analytic theory on near-spherical asteroids like 1998 KY_{26} and on more elongated and/or irregular objects like (1862) Apollo and (25143) Itokawa.

02.02 YORP-Driven Expansion of Binary Asteroid Systems

Eugene G. Fahnestock[1], D. J. Scheeres[2]
[1]*Univ. of Michigan,* [2]*Univ. of Colorado.*

We address the effect of continued YORP spin-up on the rapidly rotating primaries of the largest class of binary asteroid systems: asynchronous binaries typified by 1999 KW4. We show that this leads to the continued expansion of these systems on time scales several times faster than tidal dissipation expansion rates, and maintains the primary spin at near-critical rates. We theorize angular acceleration of the primary (due to YORP) recurringly moves it to supercritical spin, causing episodic lofting of primary regolith. Angular momentum thus added to the primary is transferred, through gravitational interaction of lofted particles with both components, into combined orbit and secondary angular momentum, producing orbit expansion. To validate these hypotheses, we first use high-fidelity dynamic simulation of particles in the full gravity field of the components, themselves propagating according to their full-detail mutual gravitation. We find final disposition (return impact, transfer impact, escape) and average particle-mass-specific angular momentum change results for dynamically simulated regolith particles lofting at different initial primary spin rates and relative poses. We use the dynamic simulation output to perform probability-based mapping of many particles on the primary surface forward in time to extreme durations at little computational cost. Tracking changes to mass, inertia dyad, rotation states, and centroid position and velocity for each component, in response to the particle motion, allows changes to the angular momenta of primary, secondary, and mutual orbit to be tracked. This clearly demonstrates the angular momentum transfer mechanism behind binary separation evolution, validating our theory. Given system parameter values for KW4, its current expansion rate is ≈0.861 m/kyr, orbit size doubling and halving times are ≈2.46 Myr and ≈1.70 Myr. Assuming 10 Mt free surface material, on-average mass lofting rate and material mass in flight are ≈0.3 kg/s and ≈173 kg, though lofting's episodic nature complicates the latter's interpretation.

02.03 **The Yarkovsky Effect in the Flora and Baptistina Asteroid Families**

Lawrence A. Molnar[1], M. J. Haegert[1]
[1]*Calvin College.*

In recent years, the distribution of orbital elements within an asteroid family has been shown to be affected both by the Yarkovsky effect and by passage across weak planetary resonances (e.g., Nesvorny et al. 2002, Icarus, 157, 155-172; Bottke et al. 2007, Nature, 449, 48-53). In extreme cases such as the Flora family, the degree of dispersion and the presence of a significant background make it difficult to reliably identify family members with standard techniques. This paper presents a new statistical approach to identifying asteroid family members that makes use of the size dependence introduced by the Yarkovsky effect.

We apply this technique to the Flora family and find the signature of the Yarkovsky effect there. We apply it to the Baptistina family and find the signature of a planetary resonance. Also, comparison of the two results yields a relative age of the two families.

Finally, we discuss how the details of family orbital evolution might be probed by an observational study of asteroid spin axes. We show that such a study is feasible for the Flora family using a modified version of the epoch method of axis determination.

02.04 **Searching for Yarkovsky Among the Near-Earth Asteroids**

Steven R. Chesley[1], D. Vokrouhlicky[2]
[1]*JPL/Caltech,* [2]*Charles University, Czech Republic.*

We report the results of a comprehensive search for evidence of the Yarkovsky effect in the orbital fits of near-Earth asteroids. The Yarkovsky effect is a subtle nongravitational acceleration on asteroids related to the anisotropic emission of thermal radiation. It has so far been directly measured in the motions of only two asteroids, 6489 Golevka [2] and 152563 (1992 BF) [1]. In past studies the Yarkovsky effect was modeled by solving the heat diffusion problem either linearly or through finite element methods. Here we take a less cumbersome and more direct approach, modeling the Yarkovsky effect as a purely transverse acceleration that is inversely proportional to the inverse square of the asteroid's heliocentric distance. The best-fitting transverse acceleration leads directly to a mean drift rate in the semimajor axis, which is the chief manifestation of the Yarkovsky acceleration. This study has revealed a number of probable detections of the Yarkovsky effect.

[1] S.R. Chesley et al., Science v. 302, 1739-1742 (2003)
[2] S.R. Chesley et al., BAAS v. 38, 591 (2006)

Session 03 Planet-Disc Dynamics

Oral, Monday, April 28, 2008, 1:45 pm - 3:30 pm

03.01I **The Co-orbital Corotation Torque and Its Effect on Planet Migration**

Frederic Masset[1]
[1]*Commissariat à l'Énergie Atomique - Saclay, France and IA-UNAM, Mexico.*

A planet embedded in a gaseous protoplanetary disk is subject to a tidal torque from the disk. When the orbit is circular, the co-orbital corotation torque corresponds to the torque arising from the material of the coorbital region. I will present the dynamics of this region, and I will present situations in which the co-orbital corotation torque plays a major role for planetary migration. Namely I will show how this torque can halt the migration of low-mass planets at the edge of a cavity, then I will turn to the case of sub-giant planets embedded in massive disks, for which migration can undergo a runaway. Finally, I will present some recent results about the properties of the co-orbital corotation torque in a radiatively inefficient disk, and I will show how the latter can halt or revert type I migration.

03.02 **Evolution of Giant Planet Orbits in a Turbulent Circumstellar Disk**

Althea Moorhead[1] *
[1]University of Michigan.

We present a parametric study of giant planet migration through the combined action of disk torques and planet-planet scattering. Disk torques exerted on planets are divided into: Type II migration effects, which readily decrease semi-major axes and orbital eccentricities, and turbulent effects, which induce a random walk in orbital elements. This paper presents parametric exploration of the possible parameter space for this evolutionary scenario using two eccentricity damping timescales (0.1 and 0.3 Myr) and varying levels of turbulence. For each class of system, many realizations of the simulations are performed in order to determine the distributions of the resulting orbital elements of the surviving planets; this paper presents the results of ~ 1200 numerical experiments. Our goal is to study the physics of this particular migration mechanism and to test it against observations of extrasolar planets. The action of disk torques and planet-planet scattering produces a wide range in semi-major axis and eccentricity, in rough agreement with observations. We find that as we increase the level of turbulence in the disk, pairs of planets are less likely to enter mean motion resonances, and fewer multiple planet systems survive.

* Student stipend winner.

03.03 **Planetary Migration in a Self-Gravitating Gaseous Disk**

Clement Baruteau[1*], F. Masset[1]
[1]CEA, France.

A planet embedded in a protoplanetary gaseous disk experiences a torque from the disk which generally leads to its orbital decay toward the central object. This process, known as planetary migration, plays a major role in the formation of planetary systems. In order to elaborate predictive scenarios, it is of primary interest to have accurate estimates of the migration timescale. Many recent works on planet-disk interaction have challenged to include more physical ingredients, but very few of them considered the disk self-gravity. In this communication, I will present the impact of the disk self-gravity on the migration rate by means of two-dimensional hydrodynamic simulations. Namely I will show that the customary practice in planet-disk simulations to consider a planet freely migrating in a disk without self-gravity induces a spurious shift of Lindblad resonances, which can lead to a significant overestimate of the torque. I will also describe additional inertial issues when a circumplanetary disk builds up around the planet.

* Student stipend winner.

03.04 **Planet Migration in Planetesimal Disks: Effects of a Gas Disk**

Chris C. Capobianco[1], M. J. Duncan[1], H. F. Levison[2]
[1]Queen's University, Canada, [2]Southwest Research Inst.

We report here on an extension of a previous study (Kirsh, Duncan, Brasser & Levison, 2008) of planetesimal-driven migration using our N-body code SyMBA (Duncan, Levison and Lee, 1998). The previous work focused on the case of a single planet of mass M, immersed in a planetesimal disk with a power-law surface density distribution and Rayleigh distributed eccentricities and inclinations. Typically ~ 10^4 to 10^6 equal-mass planetesimals were used, where the gravitational force (and the back-reaction) on each planetesimal by the Sun and planet were included, while planetesimal-planetesimal interactions were neglected. The new runs incorporate the dynamical effects of a gas disk, where the Adachi et al. 1976 prescription of aerodynamic gas drag is implemented for all bodies, and the Papaloizou & Larwood (2000) prescription of Type-I migration for the planet are implemented.

In the gas-free cases, rapid planet migration was observed -- independent of the planet's mass -- provided the planet's mass was not large compared to the mass in planetesimals capable of entering its Hill sphere. In such cases, both inward and outward migrations could be self-sustaining, but there is a strong propensity for inward migration which is related to the small inherent asymmetry in outward versus inward scattering. When a gas disk is present, aerodynamic drag can substantially modify the dynamics of scattered planetesimals. For sufficiently large or small planetesimals, the planet typically migrates inward. However, for a range of plausible planetesimal sizes, outward migration is usually triggered, often accompanied by substantial planetary mass accretion. The effects of including Type-I planet migration, and a planetesimal size spectrum will also be discussed.

Session 04 Kuiper and Oort

Oral, Monday, April 28, 2008, 3:50 pm - 5:15 pm

04.01I Resonant Dynamics of Kuiper Belt Objects and Induced Biases in Surveys

Brett Gladman[1]
[1]*Univ. of British Columbia, Canada.*

A significant fraction of known trans-neptunian objects (TNOs) are known to inhabit mean-motion resonances with Neptune. (Pluto, in the 3:2 resonance, is the best known example). Recent work has shown that many other resonances are also populated (most especially the 6:5, 4:3, 7:4, 2:1, and 5:2). The resonance dynamics cause TNOs librating in the resonance to be distributed non-uniformly on the sky in the sense that the heliocentric distance becomes strongly correlated with the separation in longitude relative to Neptune. This has a strong dependence on the detectibility of resonant TNOs in observational surveys.

An important piece of the dynamics is the study of how the libration amplitude of the resonant argument enters into the observability question, since the distribution of these resonant amplitudes can be a diagnostic of how the resonance may have been populated due to planetary migration allowing the capture of non-resonant objects into the resonances early in Solar System history. The libration amplitude distribution couples with the size and eccentricity distributions to determine the sensitivity of detection when a TNO search is conducted in a certain sky direction. I will show how these considerations can be used with calibrated TNO surveys to constrain the orbital element and size distributions of resonant objects in the Kuiper Belt. This goal is considerably complicated by the fact that many high-inclination resonant TNOs also co-inhabit the Kozai resonance. Such objects have a further strong effect introduced into their detectibility.

This work is supported by NSERC, CFI, NASA-Planetary Astronomy, and the Canada Research Chairs program.

04.02 Assessing the Threat of Oort Cloud Comet Showers

Nathan A. Kaib[1], T. Quinn[1]
[1]*Univ. of Washington.*

A field star passes within 5,000 AU of the solar system once every ~100 Myrs on average. During these extremely close stellar passages large numbers of Oort Cloud orbits are modified, which drastically increases the flux of long-period comets entering the inner solar system for 2-3 Myrs. We model these stellar-induced comet showers using direct numerical simulations. We find that comet shower strength is determined by the stellar encounter details as well as the structure of the inner Oort Cloud, which is poorly constrained. Using our simulation results, we attempt to build a probability function of comet shower intensity. Knowing the probability for a comet shower of a given intensity to occur helps us to determine whether the impacts from these phenomena have significantly affected conditions on Earth's surface in the past.

04.03 **Evolution of the Inner Oort Cloud in the Current Galactic Environment**

Ramon Brasser[1], M. J. Duncan[2], H. F. Levison[3]
[1]Univ. of Toronto at Scarborough, Canada, [2]Queen's University, Canada, [3]Southwest Research Inst.

During a previous study models of the inner Oort cloud were built which included the effect of an embedded star cluster on cometary orbits about the Sun. The main conclusions were: the formation efficiency is about 10\%; the median distance of the cloud to the Sun only depends on the mean density the Sun encountered. We report on simulations which followed the dynamical evolution of these clouds in the current Galactic environment once the Sun left the star cluster. The question is whether or not the dynamical influence of passing stars and the Galactic tidal field is sufficient to replenish the current outer cloud (semi-major axis a>20000 AU) with enough material from the inner cloud (a<20000 AU). Since visible new comets come directly from the outer cloud, a mass estimate only exists for the latter, with a lower limit of 1 Me. The expansion of the inner cloud can yield an estimate of the mass of said inner cloud. Results indicate typically 10% of the comets from the inner cloud land in the outer cloud and are bound after 4.5 Gyr. If one assumes in the extreme case the majority of material in the current outer cloud came from the inner cloud, then a typical value of the mass of the inner cloud is about 10 Me. Since 10% of comets from the Jupiter-Saturn region were implanted in the inner Oort cloud, this implies about 100 Me for the mass of solids in the primordial Jupiter-Saturn region. This extreme case might be remedied as follows: either the effect of GMCs on the inner Oort cloud is much more severe than originally thought, or a two-stage formation process for the Oort cloud, in which the outer cloud was largely populated by comets once the Sun had left its primordial birth cluster.

Business Meeting

Monday, April 28, 2008, 5:15 pm - 6:45 pm

Session 05 Public Lecture. Carolyn C. Porco "At Saturn: Tripping the Flight Fantastic"

Glenn Miller Ballroom, Colorado University
Invited, Monday, April 28, 2008, 7:30 pm - 8:30 pm

05.01I **At Saturn: Tripping the Flight Fantastic**

Carolyn C. Porco[1]
[1]CICLOPS, Space Science Inst.

Boulder planetary scientist Carolyn Porco, leader of the imaging team for NASA's Cassini mission to Saturn and science advisor for the forthcoming movie "Star Trek," guides you on a magical mystery tour around the ringed planet. Come and witness the wonders, discoveries, and the awesome natural beauty of this amazing planet and its family of rings and moons.

TUESDAY, 29 April 2008

Session 06 Extrasolar Planets

Oral, Tuesday, April 29, 2008, 8:20 am - 10:40 am

06.01 Measuring Interior Properties of Very Hot Jupiters Through Transit Timing

Darin Ragozzine[1], A. S. Wolf[1]
[1]*Caltech.*

The radius of an extra-solar planet is measured photometrically when the planet transits its parent star. Many of these planets have anomalously large radii, while others are extremely compact. Despite many theoretical efforts, these radius anomalies are still unexplained, though they clearly depend on the diversity of planetary interiors. We show that the currently unknown interior properties of extra-solar planets can be directly measured by observing the orbital precession induced by the quadrupole moment of the planet as evidenced by subtle but observable changes in the transit light curves (Ragozzine & Wolf, 2008, ApJ, pending submission). Other authors have suggested using transit timing to observe the effects of general relativity, stellar oblateness, or additional planets in the system. We show that precession due to the quadrupole moment of the planet dominates over other perturbations by 1-2 orders of magnitude in the case of single very hot Jupiters ($a \simeq 0.02$ AU). We assess the realistic measurement accuracy of extra-solar gravitational moments (e.g. J_2) and find that it is a sensitive function of eccentricity, but clearly measurable for reasonable eccentricities ($e < \sim 0.01$). We will discuss the capabilities of this new technique to directly characterize the diversity of extra-solar planet interiors in light of future observations, particularly those provided by the Kepler space-based photometry mission.

06.02 Searching for Planets using Particle Swarm Optimization

John E. Chambers[1]
[1]*Carnegie Institution of Washington.*

The Doppler radial velocity technique has been highly successful in discovering planetary-mass companions in orbit around nearby stars. A typical data set contains around one hundred instantaneous velocities for the star, spread over a period of several years,with each observation measuring only the radial component of velocity. From this data set, one would like to determine the masses and orbital parameters of the system of planets responsible for the star's reflex motion. Assuming coplanar orbits, each planet is characterized by five parameters, with an additional parameter for each telescope used to make observations, representing the instrument's velocity offset. The large number of free parameters and the relatively sparse data sets make the fitting process challenging when multiple planets are present, especially if some of these objects have low masses. Conventional approaches using periodograms often perform poorly when the orbital periods are not separated by large amounts or the longest period is comparable to the length of the data set. Here, I will describe a new approach to fitting Doppler radial velocity sets using particle swarm optimization (PSO). I will describe how the PSO method works, and show examples of PSO fits to existing radial velocity data sets, with comparisons to published solutions and those submitted to the Systemic website (http://www.oklo.org).

06.03 **Survival and Detectability of Exoplanets Beyond 100 AU**

Dimitri Veras[1], J. R. Crepp[1], E. B. Ford[1]
[1]*Univ. of Florida.*

Direct imaging searches have begun to achieve significant sensitivity to giant planets at large separations (> 100 AU) from their host stars. Such searches motivate the exploration of planetary formation and evolution models that predict the number, masses, and orbital properties of planets which may reside in wide orbits. The standard formation models of core accretion and direct gravitational collapse are not expected to form such planets in situ. We explore the possibility of giant planets forming at conventional distances before migrating to much larger separations via gravitational scattering (Debes and Sigurdsson 2006). We present simulations of dynamically unstable multiple planet systems in order to determine the efficiency of placing planets on detectably wide orbits. We also investigate how long planets can remain in such "extreme" orbits and consider the effects of galactic tides and stellar encounters. We find that planet scattering could lead to a population of highly eccentric ($e > 0.8$) planets with planet-star separations of hundreds to thousands of AU and contrast ratios suitable for detection via direct imaging in nearby star forming regions. If most stars form multiple giant planets that will eventually undergo a dynamical instability, then the frequency of such planets could be measured via ground-based direct imaging campaigns and place constraints on planet formation models.

06.04 **Turbulence in Extrasolar Planetary Systems Implies that Mean Motion Resonances are Rare**

Fred C. Adams[1], G. Laughlin[2], A. M. Bloch[1]
[1]*Univ. of Michigan,* [2]*Univ. of California, Santa Cruz.*

This talk discusses the effects of turbulence on mean motion resonances in extrasolar planetary systems and argues that systems rarely survive in a resonant configuration. A growing number of systems are reported to be in resonance, which is thought to arise from the planet migration process. If planets are brought together and moved inward through torques produced by circumstellar disks, then disk turbulence can act to prevent planets from staying in a resonant configuration. We study this process through numerical simulations and via analytic model equations, where both approaches include stochastic forcing terms due to turbulence. We explore how the amplitude and forcing time intervals of the turbulence affect the maintenance of mean motion resonances. If turbulence is common in circumstellar disks during the epoch of planet migration, with the amplitudes indicated by current MHD simulations, then planetary systems that remain deep in mean motion resonance are predicted to be rare. Specifically, the fraction of resonant systems that survive over a typical disk lifetime of 1 Myr is less than 0.025. If mean motion resonances are found to be common, their existence would place tight constraints on the amplitude and duty cycle of turbulent fluctuations in circumstellar disks. These results can be combined by expressing an upper limit on the fraction of surviving resonant systems in the form $P \approx C / \sqrt{N}$, where C is a dimensionless parameter of order unity and N is the number of orbits for which turbulence is active. [This work was supported by NASA through the Origins of the Solar System Program.]

06.05 **The OGLE-2006-BLG-109L Planetary System: Prospects for a Habitable Planet**

Renu Malhotra[1], D. A. Minton[1]
[1]*Univ. of Arizona.*

The extrasolar system OGLE-2006-BLG-109L is the first multiple-planet system to be discovered by gravitational microlensing (Gaudi et al., 2008). This system has been described as an analog for our own solar system because the two large planets that have been detected have mass ratios, semimajor axis ratios, and equilibrium temperatures that are similar to those of Jupiter and Saturn, but the system is more compact than our own because the mass of the star

is only ~0.5 $M_{\odot}$. We consider the orbital dynamics and calculate possible architectures that could support a habitable planet in the OGLE-2006-BLG-109L system.

The authors acknowledge support from NASA's Origins of Solar Systems research program and from the NASA Astrobiology Institute's University of Arizona node.

06.06 On the Origins of Eccentric Close-in Planets

Soko Matsumura[1], G. Takeda[1], F. A. Rasio[1]
[1]*Northwestern University.*

Strong tidal interaction with the central star can circularize the orbits of close-in planets. With the standard tidal quality factor Q of our solar system, estimated circularization timescales for close-in extrasolar planets are typically shorter than the lifetime of the host stars. While most extrasolar planets with small orbital radii (a<0.1 AU) have nearly circular orbits, recent observations have revealed a handful of planets with substantially large orbital eccentricities. This new class of "eccentric close-in planets" implies that either the tidal Q factor is underestimated, or the orbital circularization is prevented by other perturbation mechanisms. We constrain the tidal Q factor for transiting extrasolar planets by comparing the circularization timescales with accurately determined stellar ages. Using the estimated secular perturbation timescales, we also provide constraints on the properties of hypothetical secondary planets exterior to the known eccentric close-in planets.

06.07 Tidal Dynamics of Transiting Extrasolar Planetary Systems

Daniel C. Fabrycky[1]
[1]*Harvard-Smithsonian Center for Astrophysics.*

The transits of extrasolar planets have revealed a wealth of information about their structures and atmospheres. Because of increased transit likelihood, these planets have small semi-major axes; therefore the planets we know the best are those which are tidally evolved. Transiting planets have not yet been found in multiple-planet systems, but will eventually be an excellent probe of their dynamics. This talk addresses both sides of the coin: theories of tidal dynamics on the one side, clever observations to constrain those theories on the other. On the theory side: Small orbits may be established via eccentricity pumping by a third body (e.g., Kozai cycles) plus tidal dissipation; (b) Oblique spins (Cassini states) may be created and maintained through a secular resonance between orbital precession and spin precession; and (c) Second planets may evolve out of coorbital configurations (near Lagrange points) and mean motion resonance (e.g., the Laplace resonance among Jupiter's satellites) by tidal dissipation. On the observation side: (a) Spectroscopic transit measurements assess the spin orientation of the host star relative to the orbit of the transiting planet; (b) Transit timing measurements can discover second planets and characterize the dynamics of resonant planetary systems; (c) The instantaneous orbital configuration of two-planet systems can indicate the precession rate of the transiting planet, yielding its Love number and probing its internal structure. I gratefully acknowledge funding by the Michelson Fellowship, supported by the National Aeronautics and Space Administration and administered by the Michelson Science Center.

Session 07 Black Holes

Oral, Tuesday, April 29, 2008, 11:00 am - 12:25 pm

07.01I **Black Holes and the Evolution of Galaxies**

Douglas O. Richstone[1]
[1]Univ. of Michigan.

I will review the evidence for the ubiquitous presence of supermassive black holes in galaxies and their likely participation in the merger hierarchy associated with galaxy formation. Black hole luminosity competes with stellar luminosity in the energy budget of young galaxies. Black hole mergers may be directly detectable in gravitational waves with the proposed LISA mission.

07.02 **Dynamical Friction of Black Hole Pairs at Gas-Rich Galactic Nuclei**

Hyosun Kim[1], W. Kim[1], F. J. Sánchez-Salcedo[2]
[1]Seoul National University, Republic of Korea, [2]Universidad Nacional Autónoma de México, Mexico.

When galaxies merge, their host black holes are believed to coalesce quickly, through gas-dynamical friction, to the point at which gravitational radiation becomes important. A black hole in a binary system certainly experiences dynamical friction due to its own wake as well as due to the wake induced by its companion, but to date little is known about the role of the companion in the coevolution of black hole binaries. We use a semi-analytic approach to study the composite wake due to, and the resulting drag forces on, a point-mass black hole binary orbiting at the opposite sides of the system center in a uniform gaseous medium. Due to the circular orbit, the wake of each black hole becomes asymmetric with a trailing spiral shape, which not only drags the black hole backward but also exerts a positive torque on the companion. The ratio of the positive torque from the companion to the negative torque due to its own wake is ~0.4-0.5 and becomes larger for subsonic cases. This suggests that the orbital decay of black holes in a binary system can take considerably longer than in isolation, especially in the subsonic regime. This work was supported by KICOS through the grant K20702020016-07E0200-01610 provided by MOST, and partly for H. Kim by the BK21 project of the Korean Government.

07.03 **Fingerprints of Intermediate Mass Black Holes in Globular Clusters: Quenching of Mass Segregation**

Michele Trenti[1], M. Gill[2], C. Miller[2], D. P. Hamilton[2], R. van der Marel[1]
[1]STScI, [2]Univ. of Maryland.

Globular clusters seem to be the best place to search for Intermediate Mass Black Holes (IMBHs), but so far no definitive observational evidence for their existence has been found. Here we show that the evolution of a star cluster is strongly influenced by the presence of a central black hole, as dynamical interactions within the core prevent the development of strong mass segregation. We will present the results from a large set of direct N-body simulations of star clusters that include an intermediate mass black hole (IMBH), single and binary stars. While previous investigations have focused on the impact of an IMBH on the cluster dynamics or brightness profile, we show here that there also is an important signature on the variation of the mass function between the center and the half light radius. This measure will be accessible in the near future thanks to a large HST treasury survey of more than 50 globular clusters and will allow us to identify the best candidates to harbor an IMBH.

Session 08 The Solar System: Stable or unstable? Chaotic or non-chaotic?

Oral, Tuesday, April 29, 2008, 1:40 pm - 3:00 pm

08.01 An Investigation of the Stability of Systems of Earth-Mass Bodies Orbiting a Sun-Like Star

Andrew W. Smith[1], J. J. Lissauer[2]
[1]Stanford University, [2]Space Science and Astrobiology Division, NASA Ames Research Center.

An investigation of the stability of systems of Earth-mass bodies orbiting a sun-like star has been conducted for virtual times reaching 10 billion years. The primary motivation for this study is to characterize the maximum packing density of such bodies in the habitable zone around a star. The integrator package HNBody was utilized to carry out the integrations. For the majority of the tests, a symplectic integrator with a fixed time-step of between 1.5 and 10 days was utilized; however, smaller time-steps as well as a Bulirsch-Stoer integrator were also selectively utilized to increase confidence in the results. The planets were started on initially coplanar or nearly coplanar, circular orbits, and the longitudinal initial positions of neighboring planets were widely separated. The planets were initially uniformly spaced in distance from the sun at the start of a test. The spacing of the planets in distance from the sun was varied in multiples of their mutual Hill radii between tests. The stability time was taken to be the time at which the orbits of two or more bodies crossed; that is, the radial distance at apoapsis of an inner planet became greater than the radial distance at periapsis of an outer planet. The effect of a Jupiter-type body in the system on the resulting stability has been investigated as has the effect of decreasing the planetary masses relative to the central star. Tests have been carried out for various numbers of planets. Chaos tests were performed by slightly altering the planetary masses and by varying the initial inclinations by 0.01 degrees.

08.02 On the Dynamical Stability of the Solar System

Konstantin Y. Batygin[1], G. Laughlin[1]
[1]Univ. of California, Santa Cruz.

A long-term numerical integration of the classical Newtonian approximation to the planetary orbital motions of the full Solar System (sun + 8 planets), spanning 20 Gyr, was performed. The results showed no severe instability arising over this time interval. Subsequently, utilizing a bifurcation method described by Jacques Laskar, two numerical experiments were performed with the goal of determining dynamically allowed evolutions for the Solar System in which the planetary orbits become unstable. The experiments yielded one evolution in which Mercury falls onto the Sun at ~1.261Gyr from now, and another in which Mercury and Venus collide in ~862Myr. In the latter solution, as a result of Mercury's unstable behavior, Mars was ejected from the Solar System at 822Myr. We have performed a number of numerical tests that confirm these results, and indicate that they are not numerical artifacts. Using synthetic secular perturbation theory, we find that Mercury is destabilized via an entrance into a linear secular resonance with Jupiter in which their corresponding eigenfrequencies experience extended periods of commensurability. An application of the bifurcation method to the outer Solar System (Jupiter, Saturn, Uranus, and Neptune) showed no sign of instability during the course of 24Gyr of integrations, in keeping with an expected Uranian dynamical lifetime of 10^{18} years.

08.03 High Degree of Freedom Dynamics, Weak Chaos, and the Outer Solar System

William I. Newman[1], P. Sharp[2], K. R. Grazier[3]
[1]UC, Los Angeles, [2]University of Auckland, New Zealand, [3]Jet Propulsion Laboratory.

Sussman and Wisdom [1992] found that the outer Solar System is chaotic with a Lyapunov time of seven to twenty million years. The shortness of this Lyapunov time stimulated research on the long-term behaviour of the outer Solar System. Three important results have emerged from this research. First, for long-term simulations using symplectic methods, the timestep must be noticeably smaller than previously thought to ensure qualitative information such as the existence of chaos is correct. For example, Grazier et al. (1999) using more accurate integration approach observed that chaotic behavior disappeared when a sufficiently small time step was employed. Second, changes in the initial conditions of the order of the uncertainty in the DE405 ephemeris can create or remove chaos. Third, our models of the outer Solar System may be insufficiently robust to provide reliable information about the long-term behavior. Another aspect of the modelling that must be considered is that any realistic model of the Solar System will be a high dimensional dynamical system. This high dimensionality means the standard definitions and techniques used in chaos theory are not immediately applicable. This complication has been observed in other well-known dynamical systems, such as the Fermi-Pasta-Ulam problem (Berman and Izrailev, 2005). We show that these insights may be relevant to the simple outer solar system that is often employed, but leaves open the question of the behavior of our solar system complicated by other influences ranging from the presence of small bodies to other dynamical effects.

G.P. Berman and F.M. Izrailev (2005) Chaos 15, 015104-1-18
K.R. Grazier, W.I. Newman, W.M. Kaula, and J.M. Hyman (1999). Icarus 140, 341-352.
G.J. Sussman and J. Wisdom (1992). Science 257, 56-62.

08.04 Solar System: Surfing the Edge of Chaos Part II

Wayne B. Hayes[1], C. M. Danforth[2]
[1]UC, Irvine, [2]University of Vermont.

The orbital positions and masses of the Jovian planets are known only to a few parts in 10^7. At the 2006 DDA meeting in Halifax, I presented results, recently published in *Nature Physics* and *MNRAS*, which demonstrated the existence of both chaotic and near-regular orbits within the current observational error volume. In this talk, joint work with Chris Danforth of the University of Vermont, we present results demonstrating extremely rich structure of Lyapunov times within the uncertainty volume across many two-dimensional slices through initial-condition space. These slices include the Cartesian product of every pair of orbital semi-major axes a_p, plus Cartesian products between a_p and eccentricity e_p for each Jovian planet p. Some of the observed structure is reminiscent of Guzzo's "Web of 3-body resonances", although it is not clear that 3-body resonances are the cause in this case since the structure extends several orders of magnitude below the scale at which Murray + Holman's 3-body resonance theory has been explored. Some of the structure is entirely *unlike* that seen in Guzzo's Web, and may require further theoretical development to understand. Finally, several "zoom-in" plots, reminiscent of those done for the Mandelbrot set, demonstrate that the structure continues down, at least, to scales of about one part in 10^9.
In all cases, we verify the reliability of our integrations using convergence tests to demonstrate that the picture does not change even when the integration timestep is decreased significantly.

Session 09 Celestial Mechanics

Oral, Tuesday, April 29, 2008, 3:20 pm - 5:20 pm

09.01 Relative Equilibria in the Sphere-Restricted Full 2-Body Problem

Daniel J. Scheeres[1]
[1]*Univ. of Colorado.*

Equilibrium conditions for a mutually attracting general mass distribution and point mass are derived and their stability computed. This ``sphere-restricted'' problem is a simplification of the more difficult problem of finding the relative equilibrium and stability of two arbitrary mass distributions relative to each other. The main difficulty comes about in the loss of symmetry in the mass distributions, which removes certain analytical simplifications and forces the development of more robust equilibrium conditions. However, inclusion of these non-symmetric effects is important if one is to understand the evolution of real proto-binary systems and evaluate estimated asteroid shapes using these theories.

The equilibrium conditions can be reduced to six equations in six unknowns, plus the existence of four integrals of motion consisting of the total angular momentum and energy of the system. There are various methods for further reducing the equilibrium conditions to two independent equations. We have developed a methodology for computation and stability evaluation of relative equilibrium that directly uses energy variations at constant levels of angular momentum (Scheeres, Celestial Mechanics 94: 317--349, 2006). This methodology provides us with a rigorous and implementable approach to these difficult computations, and is a promising direction for robustly finding the relative equilibria between two non-symmetric bodies. The method is applied to estimated non-symmetric asteroid shape models of interest. Explicit conditions for the spectral and energetic stability of the resulting equilibria are also derived and computed.

This research was funded in part by a grant from the NASA Office of Space Science Planetary Geology and Geophysics Program.

09.02 Tidal Torques. Critical Review of Some Techniques.

Michael Efroimsky[1], J. G. Williams[2]
[1]*U.S. Naval Observatory,* [2]*Jet Propulsion Laboratory, California Institute of Technology.*

We compare two derivations of a popular formula for the tidal despinning rate, and emphasise that both are strongly limited to the case of a vanishing inclination and a certain (sadly, unrealistic) law of frequency-dependence of the quality factor. One method is based on the MacDonald torque, the other on the Darwin torque. Fortunately, the second approach is general enough to accommodate both a finite inclination and the actual rheology.
We also address the rheological models with the Q factor scaling as the tidal frequency to a positive fractional power, and disprove the popular belief that these models introduce discontinuities into the equations and thus are unrealistic at low frequencies. Though such models indeed make the conventional expressions for the torque diverge for vanishing frequencies, the emerging infinities reveal not the impossible nature of one or another rheology, but a subtle flaw in the underlying mathematical model of friction. Flawed is the common misassumption that damping merely provides phase lags to the terms of the Fourier series for the tidal potential. A careful hydrodynamical treatment by Sir George Darwin (1879), with viscosity explicitly included, had demonstrated that the magnitudes of the terms, too, get changed -- a fine detail later neglected as "irrelevant". Reinstating of this detail tames the fake infinities and rehabilitates the "impossible" scaling law (which happens to be the actual law the terrestrial planets obey at low frequencies).

09.03 **Relativistic Contribution to Eccentricity Bias**

Antonio R. Mondragon[1]
[1]Colorado College.

A far exterior solution to the Schwarzschild geometry is presented which provides orbital features as relativistic corrections to the Keplerian orbits of classical mechanics. It is emphasized that geometry alone is responsible for contributions to deviations from classical orbits, including precession, reduced radial coordinate, and increased eccentricity. These purely geometric contributions to orbital properties are necessary in the understanding of many astrophysical systems, including galaxies within clusters; stars orbiting black holes at the centers of galaxies and globular clusters; and rates of physical processes relevant to the formation and evolution of galaxies and clusters. Specifically, eccentricity distributions in galaxies within clusters are strongly skewed toward high eccentricities; and dynamical friction timescales for galactic satellites are found to decrease with increasing orbital eccentricity. An equation of orbit is derived which provides a quantitative prediction for increased orbital eccentricity as a natural consequence of general relativity. This orbital equation also serves to provide qualitative understandings of more complex systems. It may be argued that a geometric contribution to eccentricity must be taken into account when explaining residual eccentricities of binary pulsars and dynamical interactions of binary systems with passing stars.

09.04 **Second-order Corrections to Time Delay and Deflection of Light Passing near a Massive Object**

Neil Ashby[1], B. Bertotti[2]
[1]University of Colorado, [2]University of Pavia, Italy.

The distance of closest approach of a light ray to a massive object is an important parameter in the comparison between theory and experiment in light deflection and time delay experiments, such as in the Cassini experiment that gives the best information to date of the spatial curvature parameter γ. However the parameter is not directly measurable. It must be calculated from other information such as the radial distances of transmitter and receiver, and the elongation or angle between the vectors from source to transmitter and to receiver. We present calculations of this parameter to second order in the ratio of the Schwarzschild mass parameter to the Newtonian distance of closest approach, in isotropic coordinates, and present second-order calculations of time delay incorporating these results. This approach differs from most other such derivations that do not calculate the distance of closest approach explicitly. Other calculations of time delay to second order are reviewed and compared. Implications for the Cassini experiment are discussed. Of particular interest are the comparison with the Jet Propulsion Laboratory's implementation of higher-order corrections in the ODP (Orbit Determination Program), as well as higher order contributions to light deflection.

09.05 **Dynamics of Planetary Systems in Counter-revolving Configurations**

Julie Gayon[1], E. Bois[1], H. Scholl[1]
[1]Observatoire de la Cote d'Azur, France.

Multi-planet systems detected until now are in most cases characterized by hot-Jupiters close to their central star as well as high eccentricities. As a consequence, from a dynamical point of view, compact multi-planetary systems form a variety of the general N-body problem (with $N > 2$), whose solutions are not necessarily known. Extrasolar planets are up to now a priori found in direct orbital motions about their host star. Besides, stabilizing mechanisms of these multi-planet systems frequently involve mean-motion resonances (MMR).

We investigate a theoretical alternative suitable for the stability of compact two-planet systems. When planets are in counter-revolving configurations (which means that one of the two planets moves on a retrograde orbit), we find that

the resulting retrograde MMRs present fine and characteristic structures particularly relevant for dynamical stability. By combining our Hamiltonian technique with our numerical method of global analysis called MIPS (Megno Indicator for Planetary Orbits), we show that retrograde resonances and their resources open a family of stabilizing mechanisms involving specific behaviors of apsidal precessions. We also point out that for particular orbital data, retrograde resonances may provide more robust stability compared to the corresponding prograde MMRs.
Fitting the HD73526 planetary system to the most recent observations, we find that counter-revolving configurations may be consistent with the observational data. In the end, we propose two feasible mechanisms that might explain the origin of systems harboring counter-revolving planets.

09.06 An Asteroid Breakup 160 My Ago as the Probable Source of the K-T Impactor

William Bottke[1], D. Vokrouhlicky[2], D. Nesvorny[1]
[1]Southwest Research Inst., [2]Charles University, Czech Republic.

The terrestrial and lunar cratering rate is often assumed to have been nearly constant over the last 3 Gy. Different lines of evidence, however, suggest the impact flux from kilometer-sized bodies increased by at least a factor of 2 over the last ~100 My. Here we report that this apparent surge was triggered by the catastrophic disruption of the Baptistina parent body, a ~170 km diameter carbonaceous chondrite-like asteroid that broke up 160 +/- 20 My ago in the inner main belt. Numerous fragments produced by the collision were slowly delivered by dynamical processes to orbits where they could strike the terrestrial planets. Using numerical simulations to model this asteroid shower, we find it is the most likely source (>90% probability) of the Chicxulub impactor that produced the Cretaceous-Tertiary (K/T) mass extinction event 65 My ago.

WEDNESDAY, 30 April 2008

Session 10 Brouwer Award Presentation and Lecture

Invited, Wednesday, April 30, 2008, 8:20 am - 9:15 am

10.01I Brouwer Lecture: Very small-scale structure in the Cold Dark Matter distribution

Simon White[1]
[1]MPI für Astrophysik, Germany.

Cold Dark Matter is apparently the dominant component of all structures larger than individual galaxies. Simulations of cosmic evolution predict that its distribution should show a very rich nonlinear structure which agrees with much (but not all) of the available observational information. Techniques for direct detection of Cold Dark Matter in cooled bolometers (for neutralinos) and resonant cavities (for axions) have advanced to the point where a positive result is within reach. In addition, the next generation of gamma-ray telescopes will be sensitive enough to detect annihilation radiation from many plausible kinds of neutralino. In all these cases, the signal to be detected depends sensitively on how the dark matter distribution is structured on meter scales or smaller. Such scales are many orders of magnitude below those that can be studied with conventional N-body methods. I will describe new techniques which may allow these issues to be addressed through simulations of evolution from fully general CDM initial conditions.

Session 11 Astrometry

Oral, Wednesday, April 30, 2008, 9:15 am - 10:20 am

11.01I Astrometry with the Hubble Space Telescope

G. Fritz Benedict[1]
[1]Univ. of Texas, Austin.

In a few years astrometry with the Fine Guidance Sensors on Hubble Space Telescope will be replaced by SIM, GAIA, and long-baseline interferometry. Until then we remain a resource of choice for sub-millisecond of arc precision optical astrometry. As examples I discuss 1) the uses which can be made of our parallaxes of galactic Cepheids, and 2) the determination of perturbation orbital elements for several exoplanet host stars, yielding true companion masses. Future results will include a calibration of the Pop II Period-Luminosity relation and tests of exoplanetary system coplanarity.

11.02 Dynamical Astronomy with SIM

Stephen C. Unwin[1]
[1]JPL/Caltech.

SIM is the Space Interferometry Mission, a flexibly-scheduled instrument for microarcsecond accuracy astrometry in the optical. The ability to measure stellar positions and parallaxes to 4 μas opens up a wide range of dynamical phenomena in modern astrophysics for study. Over a narrow field, its single measurement accuracy of 1 μas allows astrometric detection of planetary systems around a large sample of nearby stars, including Earth-mass planets orbiting in the 'Habitable Zone'.

SIM will probe our Galaxy through the dynamics of halo stars and tidal streams from dwarf spheroidal galaxies, and it will measure accurate masses for many star types, including X-ray binaries. It will have the sensitivity to detect astrometric motion in the cores of active galactic nuclei, opening up the dynamical study of accretion disks and parsec-scale relativistic jets in the optical band. In 2005, the SIM project completed its technology development. Since then, it has performed trade studies to arrive at a mission that meets the peer-reviewed science objectives and reduces cost and complexity. It is being studied by NASA as a flight mission.

The research described in this talk was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

Session 12 Capture and Impact

Oral, Wednesday, April 30, 2008, 10:40 am - 12:20 pm

12.01 Formation of The Earth Impactor and Moon

Edward Belbruno[1], J. Gott III[1]
[1]Princeton Univ.

The current standard theory of the origin of the Moon is that the Earth was hit by a giant impactor the size of Mars causing ejection of iron poor impactor mantle debris that coalesced to form the Moon. But where did this Mars-sized impactor come from? Isotopic evidence suggests that it came from 1AU radius in the solar nebula and computer simulations are consistent with it approaching Earth on a zero-energy parabolic trajectory. But how could such a large object form in the disk of planetesimals at 1AU without colliding with the Earth early-on before having a chance to grow large or before its or the Earth's iron core had formed? We propose that the giant impactor could have formed in a stable orbit among debris at the Earth's Lagrange point L_4 (or L_5). We show such a configuration is stable, even for a Mars-sized impactor. It could grow gradually by accretion at L_4 (or L_5), but eventually gravitational interactions with other growing planetesimals could kick it out into a chaotic creeping orbit which we show would likely cause it to hit the Earth on a zero-energy parabolic trajectory. This paper argues that this scenario is possible and should be further studied.

12.02 On Non-Symmetric Satellite Capture in the 3D Elliptic Restricted Three-Body Problem

Marc A. Murison[1]
[1]*U.S. Naval Observatory.*

Irregular satellite capture is studied in the context of the three-dimensional elliptic restricted three-body problem. Distributions of heliocentric orbits that lead to longer capture times are found. Unlike previous studies, which begin numerical integrations around the planet and take advantage of symmetry to find a subset of heliocentric capture orbits, here we consider the fully asymmetric case. Integrations starting near the planet are carried out both forward and backward. Those ending in escapes at both ends into heliocentric orbits are temporary captures free from symmetry restrictions and represent an unbiased distribution. Use of genetic algorithm optimization techniques yields preferentially long capture times chosen from random (satellite-centered) orbital element distributions. Fractal capture-time phase space structures from the symmetric problem, which consist of sticky tori surrounding periodic orbit family characteristic curves, are preserved in the asymmetric case.

12.03 The Stability and Dynamics of Planets in Tight Binary Systems

Lamya A. Saleh[1], F. A. Rasio[1]
[1]*Northwestern University.*

The discovery of planets in tight binary systems has raised new challenges to theories of stellar and planetary formation. The most likely formation scenario for such systems involves a dynamical capture mechanism. After such a capture, high relative inclinations are likely and may lead to Kozai oscillations. We numerically investigate the fate of planets which may have been orbiting the primary before acquiring a stellar companion by performing dynamical integrations for representative four-body systems composed of a tight binary with separation ~10 AU, a hot Jupiter, and a second planet on a wider orbit, both orbiting a single star. We find that such a system can remain stable at low relative inclinations (< 40 deg) including a potentially habitable planet.

In systems with high relative inclinations, Kozai oscillations in the outer planetary orbit always lead to instabilities, except for a stability zone within which mutual gravitational perturbations among the planets can suppress the Kozai mechanism. During Kozai oscillations in the outer orbit, a differential nodal precession among planets is ensued breaking their coplanarity and mutual inclinations can grow considerably on secular time-scales. This has the potential to induce Kozai oscillations in the inner orbit if the time-scales associated with these oscillations is comparable to general relativistic (GR) precession time-scales.

Propagating perturbations from the stellar companion through a planetary system in this manner can have dramatic effects on the dynamical evolution of planetary systems and can offer a reasonable explanation of eccentricity trends among planets observed in binary systems.

12.04 Chaotic Capture of Planetesimals into Regular Regions of the Solar System. I: The Kuiper Belt

Alessandro Morbidelli[1], H. F. Levison[2], C. Van Laerhoven[3], R. Gomes[4], K. Tsiganis[5]
[1]CNRS, France, [2]Southwest Research Inst., [3]Univ. of British Columbia, Vancouver, Canada, [4]Obsevatorio Nacional, Rio de Janeiro, Brazil, [5]Univ. of Thessaloniki, Greece.

Adiabatic capture of particles in resonances is a subject widely covered in classical celestial mechanics, that has several applications in planetary science. Here we propose a new mechanism of interest for planetary science applications: the chaotic capture.

Chaotic capture occurs when, due to the change of some parameter of the system, a region of phase space becomes temporarily chaotic, before returning to a stable dynamical regime. The particles traveling freely in the chaotic sea, can reside temporarily in the concerned phase space region when the latter is chaotic, building there a steady state population of transient objects. When the region becomes regular, part of this population remains `frozen', that is permanently captured.

We discuss an application of this process for what concerns the origin of the Kuiper Belt in the framework of the `Nice' model of evolution of the giant planets. This model is characterized by a short, but violent, instability phase, during which the planets were on large eccentricity orbits. One characteristic of this model is that the original proto-planetary disk had to be truncated at roughly 30 to 35 AU. As a result, the Kuiper belt would have initially been empty. We show that the Kuiper belt is totally unstable when Neptune's eccentricity is of order of 0.2. Thus, chaotic capture can work, and objects from the region interior to ~35 AU can be implanted into the Kuiper belt without excessive inclination excitation. Assuming that the last encounter with Uranus delivered Neptune onto a low-inclination orbit with a semi-major axis of ~27 AU and an eccentricity of ~0.3, and that subsequently Neptune's eccentricity damped in ~1 My, our simulations reproduce the main observed properties of the Kuiper belt at an unprecedented level.

12.05 Chaotic Capture of Planetesimals into Regular Regions of the Solar System. II: Embedding Comets in the Asteroid Belt

Harold F. Levison[1], W. Bottke[1], M. Gounelle[2], A. Morbidelli[3], D. Nesvorny[1], K. Tsiganis[4]
[1]SwRI, [2]Lab. d'Etude la Matiere Extraterrestre Museum National d'Histoire Naturelle, France, [3]Obs. de la Cote d'Azur, France, [4]Univ. of Thessaloniki, Greece.

The main asteroid belt, which inhabits a relatively narrow annulus ~2.1-3.3 AU from the Sun, contains a surprising diversity of objects ranging from primitive ice/rock mixtures to igneous rocks. The standard model used to explain this assumes that most asteroids formed *in situ* from a primordial disk that experienced radical chemical changes within this zone. Here we continue our study of *chaotic capture* in the solar system (see abstract by Morbidelli et al. in this volume) and show that at least some of this variation was produced by dynamical processes, namely the capture of numerous comets in the outer belt during a violent period of planetary orbital evolution. These results fundamentally change our view of the asteroid belt because they imply that the observed diversity says as much about the dynamical processes of planet formation as it does about the intrinsic variation of the proto-planetary disk. The captured comets, composed of physically weak, organic-rich primitive materials, would have been more susceptible to collisional evolution than typical main belt asteroids. Accordingly, while our numerical results indicate comets once dominated the outer main belt, they have since been reduced by collisions over billions of years to a few tens of percent of the present-day population. Their weak nature makes them a prodigious source of micrometeorites - sufficient to explain why most are primitive in composition and are isotopically different from most macroscopic meteorites.

Session 13 Satellites

Oral, Wednesday, April 30, 2008, 1:35 pm - 2:35 pm

13.01 The 3-dimensional Rotation of Titan, and the Possibility of a Resonant Wobble

Benoit Noyelles[1], A. Lemaître[1], A. Vienne[2]
[1]University of Namur, Belgium, [2]IMCCE - University of Lille, France.

We performed a 3-dimensional theory of the rotation of Titan, seen as a rigid body. Using an analytical model, we determine the frequencies of the free librations around the exact Cassini state, which are respectively 2.1, 167 and 306 years. Then we use the numerical tool and the complete ephemerides (TASS 1.6) of the orbital motion of Titan to give a complete 3-dimensional theory of the rotation of Titan, given in a synthetic form thanks to frequency analysis.

This study allows us to detect a likely resonance forcing the wobble of Titan. This resonance is being studied analytically, and we show that it could force the wobble of Titan of several degrees.

13.02 Orbital Resonances during Tidal Heating of Icy Satellites

Ke Zhang[1], F. Nimmo[1], E. Chen[1]
[1]University of California, Santa Cruz.

Tides raised by the primary on a synchronized satellite result in heating if the satellite is in an eccentric orbit (Peale et al. 1979). The satellite's orbit, however, is circularized by tidal torques. The corresponding eccentricity damping timescale is usually short compared to the age of the Solar System (a few to several hundred million years for the jovian and saturnian moons). Thus tidal heating scenarios generally require additional mechanisms to maintain sufficient eccentricities, for which orbital mean-motion resonances are natural candidates (e.g. Peale et al. 1979, Showman et al. 1997). The degree of tidal heating depends on the internal structure of the satellite, which in turn depends on the body's thermal evolution, resulting in complicated feedbacks (Ojakangas and Stevenson 1986, Showman et al. 1997, Hussmann and Spohn 2002). We investigate the interaction between mean-motion resonances and satellite thermal evolution, with applications to Saturn's icy moons.

Previous studies showed that the competition between resonances and tidal circularization can lead to either an equilibrium state (Yoder and Peale 1981, Meyer and Wisdom 2007) or an oscillation around the equilibrium (Ojakagas and Stevenson 1986). Our preliminary results imply that in some circumstances, however, such an equilibrium does not exist, resulting in large orbital eccentricities and high transient tidal heating rates. We also study the eccentricity evolution near resonant trappings during the heating process, and discover that in many situations, a first-order resonant encounter excites the eccentricities of both orbits simultaneously. We apply our results to Saturn's moon Enceladus and Tethys, together with thermal models for these satellites, to investigate the origin of observed features on their surfaces.

13.03 The Rotation of Janus and Epimetheus

Matthew S. Tiscareno[1], J. A. Burns[1], P. C. Thomas[1]
[1]Cornell Univ.

The rotation states of the Saturnian moons Janus and Epimetheus experience a perturbation every four years, as the moons swap orbits. The sudden change in the orbital rate produces a free libration about synchronous rotation that is subsequently damped by internal friction. Because both moons (especially Epimetheus) are significantly triaxial, their rotational dynamics are controlled by the torque on the moon's figure, rather than the torque on any Saturn-raised tidal bulge. The free libration is fast, with a frequency on the order of the orbital frequency. The damping is therefore also fast, perhaps several months for Janus but less than that for Epimetheus. The quick libration frequency also results in a small libration amplitude, with the long axis differing by only a fraction of a degree from the sub-Saturn point, which is well below the current limits for detection by Cassini Imaging.

Janus and Epimetheus also have small orbital eccentricities which give rise to forced librations about their synchronous rotation states. For Janus, the forced libration is even smaller in amplitude than the free libration. For Epimetheus, the forced libration amplitude is several degrees, approaching the limits of detectability. Measurement of this forced libration would place a constraint on the moon's moments of inertia, as has been done for Mars' Phobos.

Session 14 Asteroids and Main-Belt Comets

Oral, Wednesday, April 30, 2008, 2:55 pm - 4:35 pm

14.01 Regulation of Primary Spin Rate of Asynchronous Binary Asteroids by "Tidal Saltation"

Alan W. Harris[1], E. G. Fahnestock[2], P. Pravec[3]
[1]Space Science Inst., [2]Univ. Michigan, [3]Ondrejov Observatory, Czech Republic.

For asynchronous binary asteroids, the primary is spinning at close to the rate where centrifugal force cancels gravity at the equator. The time varying tidal acceleration from the satellite may nearly cancel, or even reverse, the total acceleration vector on the equator as it passes directly under the satellite. We numerically investigate mass motion of loose regolith under these conditions, using parameters of binary NEA (66391) 1999 KW4, with coefficients of static and sliding friction typical of regolith materials. The onset of mass motion and even levitation off the surface begins when the tidal acceleration is not quite enough to reverse the static acceleration at the sub-satellite point. Sliding motion in the direction of the rising satellite begins when the satellite has risen about half way to the zenith. The added velocity results in the material levitating off the surface and following a ballistic trajectory for a time, re-impacting on the surface after the satellite has passed overhead and is now retarding the levitated matter, causing it to fall back. From the surface of the satellite, the levitated regolith follows a looping trajectory, falling back to a point behind where it launched, opposite the direction of rotation. Viewed from the satellite, the mass motion is a sort of standing wave, like sand saltation at the crest of a sand dune. It also resembles a tidal bulge, but with a "lag angle" close to 45 degrees, maximum for transfer of angular momentum from the spin of the primary to the orbit of the secondary. We suggest that this is the main process by which YORP torque received by the primary is transferred to the orbit of the secondary, thereby regulating the primary spin to very near the critical spin rate, and also producing the smooth "racetrack" profile of the equator.

14.02 Long-Lived Dynamical Niches in the Inner Solar System

Matija Cuk[1]
[1]Univ. of British Columbia, Canada.

Despite recent theoretical advances (Gomes et al. 2005, Chambers 2007) the cause of the Late Heavy Bombardment (a.k.a. Lunar Cataclysm) is still controversial. During the LHB, which ended by 3.8 Gya (with no clear start date; Chapman et al. 2007) multiple large impact basins formed on the Moon, and there is some evidence of bombardment on Earth, Mars and Vesta. While leading theories prefer late depletion of the main asteroid belt, trace element data in lunar soils point to overwhelmingly enstatite chondrite impactors, usually associated with the inner solar system. Bottke et al.(2007) have shown that even high-inclination planet-crossing planetesimals decay too fast to be a

viable source of the LHB. However, there exist several stable niches, potentially relevant to the LHB. We show that putative Vulcanoids and Earth-Mars-belt asteroids (Evans and Tabachnik 1999) are not plausible sources of the LHB, and that the apparent complete depletion of those regions is likely due to YORP and Yarkovsky effects, rather than any purely dynamical causes. The region between Mars and the asteroid belt does offer a long-term refuge, the stability of which depends crucially on the long-term behavior of Mars's eccentricity (cf. Chambers 2007). If Mars originally had a more circular orbit (long term $e < 0.09$), small bodies could survive in this region until chaotic dynamics excites martian eccentricity (Laskar 1989, 2008). This scenario is very similar to the "Planet V" hypothesis (Chambers 2007), only that the planet never formed. The amount of mass required for the LHB is roughly similar to that of the asteroid belt, implying much higher small-body density in the transmartian region. This is still a negligible fraction of the material needed to form the inner planets, and would require that this region was not swept by the nu_6 secular resonance, unlike the main belt.

14.03 Sweeping Resonances in the Main Asteroid Belt and the Late Heavy Bombardment

David A. Minton[1], R. Malhotra[1]
[1]*Univ. of Arizona.*

It has been proposed that the cause of the Late Heavy Bombardment (LHB) was the sweeping of resonances through the Main Asteroid Belt due to the migration of the outer giant planets. The sweeping of the ν6 secular resonance may have been an important dynamical mechanism for ejecting asteroids from the main asteroid belt into terrestrial planet-crossing orbits. Using an analytical model of the sweeping ν6 resonance and knowledge of the present day structure of the planets and of the main asteroid belt, we can place constraints on the rate of migration of Saturn, and hence a constraint on the duration of the LHB.

14.04 Asteroid Clusters in Major Mean Motion Resonances with Jupiter

Miroslav Broz[1], D. Vokrouhlicky[1]
[1]*Charles University, Czech Republic.*

We update the currently known populations of asteroids in major mean motion resonances with Jupiter - namely in the J2/1, J3/2 and J4/3 - and present their orbital and physical characteristics. We focus on an impact -generated Schubart cluster among J3/2 asteroids and we also report an identification of two new asteroids in the J4/3 resonance. We discuss their long-term evolution and possible origin. This work is supported by the Grant Agency of the Czech Republic, grant no. 205/08/P196.

14.05 Dynamics of Main Belt Comets and its Implications to Their Origins, Activation, and Possible Contribution to Earth's Water

Nader Haghighipour[1]
[1]*Institute for Astronomy, Univ. of Hawaii.*

Recent observations of icy objects in the asteroid belt have identified a new class of bodies known as Main Belt Comets (MBC). These objects that are dynamically similar to the main belt asteroids (e.g., Tisserand numbers larger than 3), present physical characteristics (e.g., dusty tails) that resemble those of comets. The discovery of Main Belt Comets has raised many questions regarding their origin, regions of existence, activation mechanism, and their possible contribution to the water on Earth. I will present the results of an extensive and systematic study of the dynamical evolution of Main Belt Comets and the mapping of their parameter-space. I will discuss the results within the context of the Nice model and in-situ formation, as possible scenarios for the origin of MBCs, and will put constraints on the models of the formation of these objects. I will also present the results of an extensive numerical study of the collision of MBCs. Observations suggest collisions between km-sized bodies and m-sized objects as a possible triggering mechanism. I will show the results of the collisions of m-sized bodies with MBCs and explain their collision probability. I will also discuss the scattering of MBCs to the inner solar system and their contribution to the formation of Earth and its water budget.

This work is supported by the NASA Astrobiology Institute under the cooperative agreement NNA04CC08A at the Institute for Astronomy at the University of Hawaii.

Session 15 Poster Session

SwRI, 1050 Walnut St., 4th floor conference room, around the corner from the St. Julien Hotel. Poster, Wednesday, April 30, 2008, 4:45 pm - 6:45 pm

15.01 On the Dynamical Stability of the Solar System

Konstantin Y. Batygin[1], G. Laughlin[1]
[1]*Univ. of California, Santa Cruz.*

A long-term numerical integration of the classical Newtonian approximation to the planetary orbital motions of the full Solar System (sun + 8 planets), spanning 20 Gyr, was performed. The results showed no severe instability arising over this time interval. Subsequently, utilizing a bifurcation method described by Jacques Laskar, two numerical experiments were performed with the goal of determining dynamically allowed evolutions for the Solar System in which the planetary orbits become unstable. The experiments yielded one evolution in which Mercury falls onto the Sun at ~1.261Gyr from now, and another in which Mercury and Venus collide in ~862Myr. In the latter solution, as a result of Mercury's unstable behavior, Mars was ejected from the Solar System at 822Myr. We have performed a number of numerical tests that confirm these results, and indicate that they are not numerical artifacts. Using synthetic secular perturbation theory, we find that Mercury is destabilized via an entrance into a linear secular resonance with Jupiter in which their corresponding eigenfrequencies experience extended periods of commensurability. An application of the bifurcation method to the outer Solar System (Jupiter, Saturn, Uranus, and Neptune) showed no sign of instability during the course of 24Gyr of integrations, in keeping with an expected Uranian dynamical lifetime of 10^{18} years.

15.02 Predicting Iridium Flares

Roger L. Mansfield[1]
[1]*Astronomical Data Service.*

At present there is a “constellation” of 66 active Iridium communications satellites and nine spares, all moving along in nearly-circular orbits at an altitude of approximately 780 km above Earth's surface. The Iridium satellites are arrayed into six orbit planes tilted 86.4 degrees to the celestial equator and spaced at equal intervals of right ascension around it. Each orbit plane contains eleven active satellites spaced at equal intervals of true argument of latitude.

Each Iridium satellite has three highly-reflective, mirror-like antennas, called “Main Mission Antennas” (MMAs), which are tilted down 40 degrees from the vertical axis of the spacecraft and spaced 120 degrees apart. Should an Earth-fixed observer be looking in the direction of one of these antennas and see the reflection of the Sun through it, he or she will observe, for a few fleeting seconds, a bright flare of sunlight that can exceed visual magnitude -8. Such a solar reflection, called an “Iridium flare,” typically happens several times a day to any Earth-fixed location, although several days may go by with no Iridium flare visible to a given Earth-fixed observer.

The attitude of each Iridium satellite is maintained on-orbit according to the following control law: "long axis down, MMA #1 forward." Since this control law dictates the precise orientation in space of each MMA at all times, it is possible to predict Iridium flares, given also that the dynamicist has in hand the current orbital elements of each Iridium satellite.

Therefore, as part of my poster presentation, I will show how to make Iridium flare predictions using the algorithms that I have developed for this purpose. I will predict the Iridium flares, if any, that can be seen from Boulder, Colorado, during each night of the DDA 2008 meeting.

15.03 Short Period Contribution In The Rotation Of Mercury

Benoit Noyelles[1], J. Dufey[1], A. Lemaître[1]
[1]*University of Namur, Belgium.*

The space missions Messenger and Bepi-Colombo require precise short-term studies of Mercury's rotation. In this scope, we performed analytically and numerically a synthetic 3-dimensional representation of this rotation, using complete ephemerides of the orbital motions of the planets. In particular, we enlight the perturbations of Venus and Jupiter. Moreover, we show that a resonance between the orbital motion of Jupiter and the free libration in longitude cannot be excluded.

15.04 The Orbits of the Neptunian Satellites and the Orientation of the Pole of Neptune

Robert A. Jacobson[1]
[1]*JPL/Caltech.*

Our previous ephemerides for the Neptunian satellites (Triton and Nereid) and our Neptune pole orientation were produced at the time of the Voyager Neptune encounter (Jacobson et al. 1991, *A&A* **247**, 565). That work was done in the B1950 reference system. Since then we have amassed a quantity of high quality Earthbased observations of the satellites. We have also reconstructed the Voyager trajectory in the International Celestial Reference Frame (ICRF). This paper reports on an update to the satellite orbits and Neptune pole based on re-fitting all of the observations used previously together with those acquired through the opposition of 2007. We now include Proteus in our satellite system as it was used for an optical navigation target in the Voyager reconstruction. The new orbits and pole are referred to the ICRF. When processing the Voyager observations we use the new ICRF Voyager trajectory.

15.05 Tidally Induced Outbursts in the Binary Black Hole System OJ287

Mauri J. Valtonen[1], K. Nilsson[1], H. J. Lehto[1], A. Sillanpää[1], L. O. Takalo[1], T. Pursimo[2], J. Heidt[3], S. Zola[4], K. Sadakane[5], J. Wu[6]
[1]*Univ. of Turku, Finland,* [2]*Nordic Optical Telescope, Spain,* [3]*Landessternwarte Heidelberg, Germany,* [4]*Jagiellonian Univ., Poland,* [5]*Osaka-Kyoiku Univ., Japan,* [6]*National Astronomical Observatories, China.*

OJ287 has been modeled as a binary black hole system [1] where the secondary impacts the accretion disk of the primary and the processes associated with the impacts lead to bursts of optical radiation. The direct impacts provide the necessary information for a unique determination of the orbital elements [2,3]. Here we discuss a secondary process where tidal torques induce an inward flow of gas in the accretion disk [4]. Some of this increased flow ends up in the jet where it causes internal shocks which appear as optical synchrotron outbursts. We have modeled the tidally induced flow by a superposition of many solutions of the relativistic three-body problem which together mimic a 10 million particle disk. The flow of disk matter through a sphere of 10 Schwarzschild radii of the primary is plotted as a function of time, and it is compared with the optical light curve over the same period of time. We find

that the “inflow light curve” and the observed light curve are very similar. In particular, the late November 2007 outburst is very well reproduced. This gives confidence in the binary black hole model and the disk/jet connection that forms the basic mechanism leading to the bright synchrotron flares.

References: 1. Sillanpää et al. 1988, ApJ 325,628; 2. Lehto & Valtonen 1996, ApJ 460,207; 3. Valtonen et al. 2008, Nature (in press); 4. Sundelius et al. 1997, ApJ 484,180

15.06 The Relationship Between Prometheus’ Mass and Azimuthal Channels’ Width.

Carlos E. Chavez[1]
[1]*Intituto de Astronomia UNAM sede Ensenada, Mexico.*

Here in this research we develop a very simple model to fit the edges of the Azimuthal Channels observed in Saturn’s F ring. This model has been used first to fit the Saturn Orbital Insertion configuration and then for the antialignment configuration. Then, since we noticed that width of the channels depend strongly in the mass of Prometheus used, the relationship between Prometheus mass and the width of the channels is found. To do so, the different masses of Prometheus that have been published are used here. The possible applications of this research such as an independent method for determining Prometheus’ mass and F ring’s core strand mass are discussed.

15.07 Nonlinear Growth of Voids Due to the Expansion of Hot Background

Peter D. Noerdlinger[1]
[1]*St Mary’s University, Canada.*

The formation of cosmic voids is generally studied via simulations that include many effects, but not the presence of a hot background (photons, neutrinos,...). As shown by P. Noerdlinger and V. Petrosian (Ap. J. 168, 1, 1971), the escape of this background as the universe expands decreases the local gravity that is trying to hold a condensation together. This behavior, also found in the linear analysis of P. Meszaros (Ap. J. 238, 781, 1980), can be carried into the nonlinear regime. If rho_cl is the density of cold matter in a condensation or overdense region, with initial value ρ_{clf}, and ρ_{light} is the density of the hot background ~ $(1+z)^4$, with initial value ρ_{lightf}, then it can be shown that $\rho_{cl}/\rho_{clf} = [(1+2\,\rho_{light}/\rho_{cl})^3] / [(1+2\,\rho_{lightf}/\rho_{clf})^3]$. This establishes that only the densest concentrations of matter, after recombination, can survive and the less dense volumes will expand with the universe, leaving the dense concentrations in the walls of the resulting voids.

15.08 Studying Reliability of Galaxy Simulations Using Shadowing

Wayne B. Hayes[1], Y. Zhu[1]
[1]*UC, Irvine.*

Numerical simulations of collisionless systems form the backbone of our theoretical understand of galaxy, cluster, and cosmological evolution. Simulation provides the crucial link between our microscopic understanding of gravity (Newtonian and Relativistic), and the macroscopic dynamical evolution of gravitational systems. Such simulations have been used to test and even invalidate theories. Thus, establishing their trustworthiness is critical. Since gravitational systems are *chaotic*, they display *sensitive dependence on initial conditions* (SDIC), so that numerical errors become exponentially magnified with time. In short order, these errors become magnified to the size of the system, leading some (eg., Heggie) to question if such simulations are the result of nothing but magnified noise. Although the existence of SDIC has been known for decades, its effect on macroscopic properties of solutions is still not yet well understood. To answer the question of their validity, we turn to the study of *shadowing*. A *shadow* is an exact solution that remains close to a numerical solution for a long time, despite the magnification of small errors. If a shadow solution exists, then the numerical solution can be viewed as an *observation* of an exact solution, and thus its dynamical properties can be trusted, to within "observational" error. In this poster, I will discuss recent results on shadowing a million-particle simulation of a collision between two galaxies. (This abstract is identical to my last year's abstract because I discovered a major flaw in my code since last year. This poster corrects the results of last year's talk.)

15.09 Radiative Thrusters on Close-in Extrasolar Planets

Daniel C. Fabrycky[1]
[1]*Harvard-Smithsonian Center for Astrophysics.*

The atmospheres of close-in extrasolar planets absorb most of the incident stellar radiation, advect this energy, then reradiate photons in preferential directions. Those photons carry away momentum, applying a force on the planet. Here the resulting secular changes to the orbit, known as the Yarkovsky effect, are evaluated. For known transiting planets, typical fractional changes in semi-major axis are about 1% over their lifetime, but could be up to ~5% for close-in planets such as OGLE-TR-56b or inflated planets such as TrES-4. Radiative thrusters are too weak by about a factor of 10 to explain the correlation between planetary semi-major axis and mass, a puzzling observational result of transit surveys which needs a dynamical explanation. However, the orbital expansion due to the Yarkovsky effect can cause interior planets to sweep exterior planets into mean motion resonance, or maintain such resonances despite the destructive influence of tidal dissipation in the planet.

15.10 Accretion Rates of Planetesimals by a Protoplanet Embedded in Nebular Gas

Takayuki Tanigawa[1], K. Ohtsuki[1]
[1]*University of Colorado, LASP.*

When the mass of a protoplanet growing in the nebular gas is large enough and it has an atmosphere around it, the gas drag by the atmosphere is expected to enhance the accretion rate of planetesimals by the protoplanet and can reduce its growth timescale. We study the effect of gas drag on the accretion rate of planetesimals by a protoplanet that has a spherical symmetric atmosphere, by analytic calculation and three-body orbital integration.

In the orbital integration, the motion of planetesimals motion is solved on Hill's coordinate using 8th-order Runge-Kutta method. We numerically integrated the motion of planetesimals with a wide range of initial random velocities.

Planetesimals experience strong gas drag when they pass close to the planet, where the gas density in higher.
For an assumed spherical gas density distribution, we obtain an analytic expression for a planetesimal's energy dissipation in a single passage through the atmosphere, and confirmed agreement with orbital integration. Using results of numerical integration of a large number of orbits, where the Rayleigh distribution of planetesimals' orbital eccentricities and inclinations are taken into account, we obtain capture rates of planetesimals for various values of the strength of gas drag.

We also obtained an analytical formula to describe the capture rates for the high random velocity regime, which agree well with the results obtained by our numerical integration. We derived an empirical formula for the capture rate which can describe the dependence of the accretion rate on random velocity, which was not considered by previous studies.

This work was supported by NASA's Origins of Solar Systems Program (NNG05GH87G) and Outer Planets Research Program (NNG05GH42G).

15.11 Solar System Astrometry at the USNO Flagstaff Station

Alice K. B. Monet[1], H. C. Harris[1], J. Hilton[1]
[1]U.S. Naval Observatory.

Beginning with the Galileo mission as it approached the asteroid Gaspra, the US Naval Observatory Flagstaff Station has collaborated closely with the JPL navigation team to provide highly accurate astrometry of various Solar System bodies that were targets of numerous spacecraft encounters. This led to the development at Flagstaff of an automated Solar System observing project, employing a small transit telescope equipped with a CCD camera (Stone et al. 1999), known as FASTT, for Flagstaff Astrometric Scanning Transit Telescope. In 2004, an astrometric survey was begun with the FASTT, with the goal of improving the orbits of all the asteroids brighter than $V_R \sim 17$. The goals of the survey also included determination of asteroid masses, rotation rates, and morphology. In addition to the brighter asteroids, certain comets, planetary satellites, and dwarf planets were included in the target list. This poster will describe the results of this survey to date, and the next phase of the project now getting underway.

15.12 Meteorite Constraints on the Early Stages of Planetary Growth in the Inner Solar System

Nader Haghighipour[1], E. Scott[2]
[1]Institute for Astronomy, Univ. of Hawaii, [2]HIGP, Univ. of Hawaii.

Being the remnants of the accretion and collision of approximately seventy 20-500 km-sized bodies, iron meteorites provide the best clues to the nature of the collisions among planetesimals and planetary embryos, and the initial stage of accretion and growth of these objects in our solar system. The parent bodies of iron meteorites were traditionally, assumed to have formed, differentiated, and subsequently been disrupted in the main asteroid belt. Observational evidence, however, does not support this assumption and indicates that differentiated bodies are currently uncommon in that area. This implies that the iron meteorites' parent bodies probably formed in the inner part of the solar system, and were scattered into the main belt through collisions and interactions with the protoplanets and the remaining planetesimals (Bottke et al 2006). An important effect that strongly influences the efficiency of this scattering is the perturbation of a growing giant planet. We have constructed a comprehensive model of the growth and scattering of meteorites' parent bodies by numerically integrating the orbits of a few thousand planetesimals and several hundred planetary embryos in the vicinity of a growing giant planet. The results of our simulations, which complement those by Bottke et al (2006), indicate a transitional range for the mass of the growing giant body ($\sim 50 M_{\oplus}$) above which the perturbative effect of this object plays a strong role in the scattering of planetesimals and decreases the efficiency of the delivery of the parent bodies of iron meteorites to the asteroid belt. I will present the details of our study and discuss the applicability of our results within the context of the core-accretion and disk instability models of giant planets formation.

This work is supported by the NASA Astrobiology Institute under the cooperative agreement NNA04CC08A at the Institute for Astronomy at the University of Hawaii.

15.13 Viscosity in Planetary Rings With Spinning Self-Gravitating Particles

Keiji Ohtsuki[1], H. Daisaka[2], H. Tanaka[3]
[1]Univ. of Colorado, [2]Hitotsubashi Univ., Japan, [3]Hokkaido Univ., Japan.

Viscosity in planetary rings arises from collisional and gravitational interactions between constituent particles. Angular momentum is transferred mainly through mutual collisions and gravitational encounters when the optical depth of the ring is low, while the formation of gravitational wakes significantly enhances the viscosity in dense rings (Daisaka, Tanaka, Ida 2001, Icarus 154, 296). On the basis of the formulation derived by Tanaka,

Ohtsuki, and Daisaka (2003, Icarus 161, 144) and using analytic calculation, three-body orbital integration and N-body simulation, we investigate viscosity in self-gravitating planetary rings, both with and without the effect of particle spins. In the case of rings with low optical depth, we confirmed agreement between results of three-body calculation and N-body simulation. When the optical depth is low and the effect of particles' mutual gravity is weak, particles' surface friction with a reasonable range of a friction parameter tends to reduce their random velocity and, consequently, viscosity as well. However, in dense rings with gravitational wakes, the effect of self-gravity is dominant. We obtain ring viscosity for a wide range of parameter values, and derive an approximate expression which reproduces our numerical results. This work was supported by NASA's Outer Planets Research Program and the Cassini Project.

15.14 Secular Evolution of Multiple Planet Systems with Ensembles of Initial Conditions

Dimitri Veras[1], E. B. Ford[1]
[1]*Univ. of Florida.*

Secular eccentricity evolution in multiple planet systems can provide particularly valuable constraints on planet formation models. Because the inevitable uncertainties in the current orbital elements can lead to significant ambiguities in the nature of the secular evolution, relevant dynamical studies should account for the uncertainties in orbital elements. By combining radial velocity observations of selected multi-planet exosystems with Markov Chain Monte Carlo techniques, we obtain ensembles of initial conditions from which to start N-body integrations that characterize secular evolution. We find that single sets of current best-fit orbital elements yield evolutionary histories which are not necessarily representative of the systems' general behavior. Our results suggest that a re-evaluation of the dynamics of multi-planet exosystems may yield fruitful insights and/or correct previous misconceptions about their orbital evolution.

15.15 Extrasolar Planet Eccentricities from Scattering in the Presence of Residual Gas Disks

Nickolas Moeckel[1], S. N. Raymond[1], P. J. Armitage[1]
[1]*University of Colorado.*

Gravitational scattering between massive planets has been invoked to explain the eccentricity distribution of extrasolar planets. For scattering to occur, the planets must either form in -- or migrate into -- an unstable configuration. In either case, it is likely that a residual gas disk, with a mass comparable to that of the planets, will be present when scattering occurs. Using explicit hydrodynamic simulations, we study the impact of gas disks on the outcome of two-planet scattering. We assume a specific model in which the planets are driven toward instability by gravitational torques from an outer low mass disk. We find that the accretion of mass and angular momentum that occurs when a scattered planet impacts the disk can strongly influence the subsequent dynamics by reducing the number of close encounters. The eccentricity of the innermost surviving planet is not substantially altered from the gas-free case, but the outer planet is circularized by its interaction with the disk. The signature of scattering initiated by gas disk migration is thus a high fraction of low eccentricity planets at larger radii accompanying known eccentric planets. The late burst of accretion when the outer planet impacts the disk is in principle observable, probably via detection of a strong near-IR excess in systems with otherwise weak disk and stellar accretion signatures.

This research was supported by NASA under grants NNA04CC11A to the CU Center for Astrobiology, NNG04GL01G and NNX07AH08G from the Astrophysics Theory Programs, and by the NSF under grant AST~0407040. S.N.R. was supported by an appointment to the NASA Postdoctoral Program at the University of Colorado Astrobiology Center, administered by Oak Ridge Associated Universities through a contract with NASA.

15.16 Evolvable Lunar Navigation and Communication Constellations

Kathryn E. Hamera[1], T. Mosher[2]
[1]University of Colorado, [2]MicroSat Systems, Inc.

Several international space agencies have announced plans for future lunar exploration missions, including orbiters, rovers, and the eventual build-up of a lunar outpost. Each of these missions will have certain communication and navigation requirements. Some missions will explore parts of the lunar environment that are not directly visible to the Earth, and a lunar relay element will be necessary to provide critical communication and navigation support. Previous research has shown the advantages of using halo orbits for a lunar relay. Halo orbit insertion costs are less than those for geostationary orbit, station-keeping costs are minimal, and the Earth is visible for 100% of the spacecraft's orbital period. An example constellation was designed to show the feasibility of a halo orbit constellation. The methodologies used to construct the example constellation can be tailored to design halo orbit constellations to meet the coverage needs of any lunar mission. Additionally, the halo orbits are selected such that low energy-transfers may be used to transfer spacecraft between halo orbits for very small maneuver costs. This follow-on research demonstrates the capability of the constellation to evolve and reconfigure through the use of low-energy transfers. Using low-energy transfers, multiple space agencies can utilize the same lunar relay constellation by reconfiguring the spacecraft to provide optimal coverage for different missions at different times. This research was funded by a grant from NASA's Exploration System Mission Directorate to the Colorado Space Grant Consortium and a Graduate Student Research Fellowship from the National Science Foundation.

15.17 Dust Motion at the Midplane in a Viscously Expanding Disk

Anna L. Hughes[1], P. J. Armitage[1]
[1]University of Colorado.

Observations of long period comet spectra have long indicated a crystalline silicate content to comet material. Also, sample return from comet Wild 2 has indicated that crystalline silicates were incorporated into this Jupiter family comet when it formed, most likely in the Kuiper belt. These results from the Stardust mission have prompted the need for a mechanism that can transport grains of at least 20 microns in size from interior to 3 AU to beyond the orbit of Neptune. Work on turbulent mixing of the solar nebula has already pointed to the viability of this mechanism for addressing the Stardust results. We explore the outward transport of dust grains of various sizes due to gas drag at the midplane in a viscously expanding protoplanetary disk. We solve for the azimuthal and radial velocities of the gas following the treatment of Takeuchi and Lin (2002, ApJ 581, 1344-1355) and examine particles in the Epstein drag regime. The disk evolves due to turbulent viscosity using the alpha-parameterization, and photoevaporation by the central star. During early disk evolution we find direct outward transport of dust grains to several tens of AU on timescales of about a million years. This research was supported by NASA under grant NNX07AH08G.

15.18 Rotational Dynamics: A Geometrical Approach

William I. Newman[1], W. B. Moore[1], B. G. Bills[2]
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The equations describing the dynamics of rotating bodies on precessing orbits are naturally treated in terms of geometric transformations (rotations) of the angular momentum vectors. Indeed, Cassini's (1693) well-known laws regarding rotation of synchronous bodies are not physical laws, but rather geometrical constraints. The physical basis for them was elucidated much later by Colombo (1966), Peale (1969), and others, and has since then been treated largely in terms of orbital elements (and associated rotational parameters) via Hamiltonian methods (e.g., D'Hoedt and Lemaitre, 2004; Yseboodt and Margot, 2006). A drawback to the typically used formulation is that dissipation does not naturally enter the problem, and is invoked mainly to drive the system toward a fixed point. If

the trajectory of the system away from the fixed points is desired, ad-hoc dissipative mechanisms may be added, but such treatments occasionally fail to conserve invariant quantities such as angular momentum. We will present analytical, closed-form solutions for a widely-employed class of models for rotating bodies on arbitrarily precessing orbits with dissipation which more clearly elucidate the role of dissipation in driving the dynamics. We will explore some possible modifications to the Hamiltonian approach that could accommodate dissipation and make the Cassini states local attractors for the system.

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Peale, S. J. 1969, Astron. J. vol. 74, 483.
Yseboodt, M. and J-. L. Margot 2006, Icarus, vol. 181, 327.

15.19 Mapping Complexity: the Wavy Edges of the Encke and Keeler Gaps in Saturn's Rings

Paul A. Torrey[1], M. S. Tiscareno[1], J. A. Burns[1], C. C. Porco[2]
[1]Cornell University, [2]CICLOPS/SSI.

The edges of the Keeler and Encke gaps of Saturn's A Ring are significantly disturbed as the embedded moons (Daphnis and Pan, respectively) interact with the adjacent dense rings. Cassini images of these edges reveal the structure to be much more complex than predicted by analytical perturbation theory (Tiscareno et al 2005, DPS). In the Encke Gap, we see both amplitude and frequency modulations of the expected monochromatic sinusoid, as well as some sharper "glitches" in the pattern. In the Keeler Gap, the expected 32-lobed pattern in the inner edge due to a resonance with Prometheus is "lumpy" and asymmetric, while the outer edge features sharp-edged asymmetric "wisps".

Much of the unexpected structure may be due to the superposition of multiple patterns, each moving with its own frequency. Determination of these pattern speeds will help us to identify the source of the perturbations, and may help us better appreciate the transfer of angular momentum between dense particle disks and embedded moons. We will present high-resolution maps of these edges covering all longitudes and at many points in time.

THURSDAY, 01 May 2008

Session 16 Rings - I

Oral, Thursday, May 01, 2008, 8:20 am - 10:20 am

16.01 Physics of Jupiter's Gossamer Rings

Douglas P. Hamilton[1], H. Krueger[2]
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Thebe's gossamer ring, the outermost and faintest of Jupiter's rings, extends outward by at least half a jovian radius from its source satellite while maintaining a constant vertical thickness. This structure is created by an electromagnetic perturbation known as a shadow resonance (Hamilton 2003, DPS meeting #35, #11.09). A shadow resonance arises from the abrupt shutoff of photoelectric charging when a dust particle enters Jupiter's shadow which, in turn, affects the strength of the electromagnetic perturbation from the planet's intense magnetic field. The

result is a coupled oscillation between a particle's orbital eccentricity and its semimajor axis. Ring material spreads outward from Thebe while maintaining its vertical thickness just as observed by Galileo imaging.

In addition to cameras, the Galileo spacecraft was also equipped with dust and plasma detectors. The spacecraft made two passes through the ring and its dust detector found that 1) dust fluxes drop immediately interior to Thebe's orbit, 2) some grains have inclinations in excess of 20 degrees and 3) submicron particles are present in the Amalthea ring in much greater numbers than in the Thebe ring. These findings can all be explained in the context of our shadow resonance model: the inner boundary is a direct consequence of the conservation of the Electromagnetic Jacobi Constant, the high inclinations are forced by a vertical version of the shadow resonance, and the excess submicron particles are a consequence of the weakening of electromagnetic forces in the vicinity of synchronous orbit. In this talk, we will present the data sets as well as detailed numerical simulations that back up these claims.

16.02 The Outer Dust Rings of Uranus in the Hubble Space Telescope

Mark R. Showalter[1], J. J. Lissauer[2], R. G. French[3], D. P. Hamilton[4], P. D. Nicholson[5], I. de Pater[6]
[1]SETI Institute, [2]NASA Ames, [3]Wellesley, [4]Univ. of Maryland, [5]Cornell Univ., [6]U. C. Berkeley.

Between early May and mid-August 2007, the rings of Uranus were oriented nearly edge-on to Earth. This provided an exceedingly rare opportunity to obtain clear views of the system's faint, outer dust rings, μ and ν. We conducted regular imaging of the Uranian system throughout this period with the Wide Field/Planetary Camera on HST. Here we present our initial results on the outer rings. We confirm earlier reports that the μ ring is blue; previously this was based on comparisons between visual data and upper limits at 2.2 μm; this could have been the result of an absorption band rather than a uniform trend. However, we find a factor-of-two drop in ring brightness between wavelengths of 0.6 to 0.8 μm; this makes the μ ring as blue as Saturn's E ring, suggesting that sub-μm particles predominate. More surprisingly, the ring shows very large variations in brightness with longitude. Variations by a factor of several over scales of tens of degrees are common. No systematic pattern has yet been identified, but it is noted that one ansa of the ring is usually darkest when the other is brightest, suggesting a periodicity with an odd number of cycles. Further investigation is needed to determine the nature of these variations. Because the ring is very broad, one would expect such variations to shear out in a time scale of weeks to months, unless these variations are confined to a much narrower radial range than is the visible ring.

16.03 Dynamics of Particles in E Rings of Saturn Near Enceladus' Orbit

Manish Agarwal[1], J. A. Burns[1], M. S. Tiscareno[1], M. M. Hedman[1]
[1]Cornell University.

Cassini observations have shown that Saturn's tenuous E Ring has a double-banded vertical structure, with the density of particles decreasing in the equatorial plane of the rings. We have conducted numerical simulations, using SWIFT, supported by order-of-magnitude analytical calculations, to investigate how the micron-sized ice particles behave in the vicinity of Enceladus' orbit to form the observed structure. Effect of Saturn, including its J_2, and Enceladus are considered.The other moons have negligible effect over the ~200- year integration. We follow the orbits of massless particles ejected from Enceladus' south pole with velocities ranging between 0.9 to 1.4 times the escape velocity at the moon's surface. Our results suggest that Enceladus causes the double-banded structure by attracting the particles towards the moon due to its gravity, that would otherwise pass at some distance away and then by eliminating the particles which collide with the moon. This creates a scarcity of particles in the equatorial plane which is manifested as a double-layered structure.

16.04 What is New in Saturn’s F Ring Azimuthal Channels?

Carlos E. Chavez[1]
[1]*Intituto de Astronomia UNAM sede Ensenada, Mexico.*

How Prometheus creates azimuthal structure in the F ring has been puzzling the scientists since these features were first observed during the Saturn Orbital Insertion (hereafter SOI) in July 2004. The SOI configuration is studied numerically with updated orbits, the plots obtained are in excellent agreement with the observed structures by Cassini spacecraft and with the numerical model we previously reported in Murray et al. 2005.
A very simple model has been developed to fit the edges of the channels in order to study their maximum width for the SOI configuration. This has helped us to understand some of the dynamics involved in their formation.
The approximate date for the antialignment configuration has been calculated, this enabled us to predict the possible appearance of the ring for this configuration. A new feature has been found (an ``island’’) that according to our numerical model should be visible during the antialignment configuration in late December 2009.

16.05 Searching for Sub-Centimeter Particles in Saturn’s Main Rings

Rebecca A. Harbison[1], P. D. Nicholson[1], Cassini VIMS Team
[1]*Cornell University.*

The shape of the particle size distribution in Saturn’s main rings has implications both for dynamical modeling of behavior within the rings, such as self-gravity wakes, and in re-accretion models of material produced by interplanetary impacts. However, previous attempts to study the sub-centimeter size distribution of ring particles have been hampered both by the paucity of particles below the centimeter scale, and by limitations in observational techniques. With the Cassini spacecraft in Saturn orbit, solar occultations by the rings can be measured using the Visual-Infrared Mapping Spectrometer. The large signal from the Sun and milliradian angular resolution in the near-infrared (1 to 5 microns) supplied by VIMS allows a direct measurement to be made of light forward-scattered from any millimeter-sized particles in the rings. Given the wavelength range and angular resolution of VIMS, and the angular size of the Sun at Saturn’s distance, particles larger than one centimeter will predominantly forward-scatter into angles too small to be separated from the solar image itself, making these observations most sensitive to smaller particles. We will provide data from several solar occultations, at ring opening angles ranging from 9 to 21 degrees. After subtracting a template based on images of the unocculted sun, we’ve searched for scattered light signals due to such particles. A small, but potentially significant, signal is seen, which requires further work to confirm, and quantify in terms of the particle-size distribution.

16.06 Cassini Observations of Lindblad Resonances in Low Optical Depth Rings.

Matthew M. Hedman[1], J. A. Burns[1], M. S. Tiscareno[1], P. D. Nicholson[1], C. C. Porco[2]
[1]*Cornell Univ.,* [2]*CICLOPS/SSI.*

Images from the Cassini spacecraft reveal several unexpected structures in Saturn’s faint rings that appear to be generated by Lindblad resonances. The clearest example of such a feature consists of a series of brightness in the outer part of the diffuse G ring that appear to be generated by the 8:7 Inner Lindblad Resonance with Saturn’s moon Mimas (These features are located 170,000 km from Saturn center, and are distinct from the bright arc in the G ring located at 167,500 km). Similar but more complex structures are found in both the D ring (the innermost part of the ring system at 65,000-74,500 km from Saturn center) and the Roche Division between the A and F rings (137,000-140,000 km from Saturn center). The locations, pattern speeds and symmetry properties of the brightness variations in the D ring are consistent with 2:1 Inner Lindblad resonances, while those in the Roche Division appear to be caused by 3:4 Outer Lindblad Resonances. At both locations, multiple perturbations with periods ranging between 10.5 and 10.9 hours appear to be affecting the ring material. This overlaps the span of periods associated with

Saturn's winds and magnetosphere, so these structures may be created by anomalies in Saturn's gravitational and/or magnetic fields. The relative strength and persistence of these patterns may therefore provide information about the structure of the planet's interior or the dynamics of the inner magnetosphere. Furthermore, all of these structures should provide new insights into how resonant perturbations affect disks of material in the regime where the disk optical depth is low and the typical particle size is small (1- 100 microns).

Session 17 Planet Formation

Oral, Thursday, May 01, 2008, 10:40 am - 12:00 noon

17.01 Accretion of Gas onto Circumstellar Disks During Planet Formation

Henry B. Throop[1], J. Bally[2]
[1]SwRI, [2]Univ. Colorado / CASA.

Young stars orbiting in the gravitational potential well of forming star clusters pass through the cluster's dense molecular gas and can experience Bondi-Hoyle accretion from reservoirs outside their individual protostellar cloud cores. Accretion can occur for several million years after the stars form, but before the cluster disperses. This accretion is predominantly onto the disk and not the star.

N-body simulations of stars orbiting in three young model clusters containing 30, 300, and 3000 stars are presented. The simulations include the gravitational potential of the molecular gas which smoothly disperses over time. The clusters have a star formation efficiency of 33% and a radius of 0.22~pc. We find that the disks surrounding solar-mass stars in the N=30 cluster accretes ~0.01 m_{sol} (1 minimum-mass solar nebula, MMSN) per Myr, with a 1 sigma width of 50 times due to variations in initial stellar positions and velocities within the cluster. The accretion rate scales as M^2.1 for stars of mass M. The accretion rate is ~5 times lower for N=3000 cluster, due to its higher stellar velocities and higher temperature. The Bondi-Hoyle accretion rates onto the disks are several times lower than accretion rates observed directly onto young stars: these two accretion rates follow the same M^2 behavior and may be linked. The accreted disk mass is large enough that it may have a substantial and unappreciated effect on disk structure and the formation of planetary systems. We discuss a variety of implications of this process, including its effect on metallicity differences between cluster stars, compositional differences between a star and its disk, the formation of terrestrial and gas-giant planets, and isotopic anomalies observed in our Solar System.

17.02 Planetesimals to Protoplanets: Effect of Dust on Terrestrial Planet Formation

Zoe Leinhardt[1], D. C. Richardson[2]
[1]University of Cambridge, United Kingdom, [2]University of Maryland.

We present results from a series of direct N-body simulations of terrestrial planet formation. These simulations focus on determining the effect of the initial dust distribution on planetesimal growth in the middle phase of planet formation. The initial conditions include a range of initial dust mass from zero to ten times the initial planetesimal mass. All planetesimals are treated as gravitational aggregates. The planetesimal collision model allows both accretion and fragmentation outcomes. The dust interacts with the planetesimals through accretion and dynamical friction.

We find that when dynamical friction from the dust is included, the evolution of the planetesimals is slower and occurs more uniformly over semi-major axis. Because the dynamical friction causes the orbits of the planetesimals to circularize, the collisions between planetesimals are slow and always result in growth. As a result, the dust is not replenished. However, the dust is not accreted quickly and remains until late times. Eventually, the eccentricity of the largest objects can not be damped by the dust but instead begins to increase along with the impact speeds.

In conclusion, we find that the middle phase of planet formation cannot produce a massive dust disk but if the debris is the result of an earlier phase it may have significant dynamical and evolutionary effects on the growth of planetesimals in the terrestrial region.

17.03 Building the Terrestrial Planets: Constraining Planetary Accretion in the inner Solar System

Sean N. Raymond[1], D. P. O'Brien[2], A. Morbidelli[3], N. A. Kaib[4]
[1]University of Colorado, [2]Planetary Science Institute, [3]Observatoire de Nice, France, [4]Univ. of Washington.

We present results of N-body simulations of planetary accretion with the goal of reproducing the inner Solar System. Planetary embryos and planetesimals evolve and grow under the influence of Jupiter and Saturn, which are assumed to have formed during the short gaseous phase of the Solar Nebula. We compare the results of these simulations to the current Solar System in order to constrain the configuration of Jupiter and Saturn at early times, analyzing cases that are both consistent and contrary to the 'Nice model.' We attempt to reproduce 1) the masses and orbits of Venus, Earth and Mars -- Mars' relatively small mass in particular has not been adequately reproduced in previous simulations; 2) the structure of the asteroid belt -- we show that a remnant embryo larger than the Moon is inconsistent with the main belt structure; and 3) the water content of the Earth, assuming that it was delivered in the form of water-rich primitive asteroidal material. We find that Jupiter and Saturn are the most important factor in the outcome, exciting asteroidal bodies via secular and mean motion resonances. A configuration with the giant planets on circular orbits can form a water-rich Earth and Venus but Mars' mass is too large by a factor of 5-10. A configuration with Jupiter and Saturn in their current locations but with slightly higher eccentricities produces Earth, Venus, Mars and the asteroid belt, but does not allow water delivery to Earth. Further simulations with a range of configurations of Jupiter and Saturn are currently underway in order to better reproduce all of the above characteristics of the inner Solar System. This will allow us to constrain Jupiter and Saturn's orbits at early times and test the validity of scenarios such as the 'Nice model.'

17.04 The Varieties of Planetary Experience

Edward Thommes[1], S. Matsumura[2], F. A. Rasio[2]
[1]University of Guelph, Canada, [2]Northwestern University.

Using a new hybrid code, we are able to perform detailed numerical simulations which span nearly the entire sequence of planet formation---from the appearance of the first protoplanets in a young gas disk, to long after the disk's dispersal. I will present some of the results we have obtained so far, which are already giving us a number of new insights into the planet formation process. Among other things, these simulations are providing clues as to how our own Solar System fits into the ensemble of planets discovered to date. This work is supported by the NSF (AST-0507727) and by the Spitzer Theoretical Research Program (Cycle-4, pid#40380).

18 Rings - II

Oral, Thursday, May 01, 2008, 12:00 noon - 2:35 pm
This session includes a brief break after presentation 18.03 from 1:00 pm to 1:15 pm.

18.01 Cassini-VIMS Observations of Self-gravity Wakes in Saturn's Rings - II

Philip D. Nicholson[1], M. M. Hedman[2], H. J. Salo[3], Cassini VIMS Team
[1]Cornell University, [2]Cornell Univ., [3]Univ. of Oulu, Finland.

Azimuthal variations in the reflectivity (at both visual and radar wavelengths), brightness temperature and optical depth of Saturn's rings have been widely observed and are generally attributed to what are now referred to as 'self-gravity wakes', as observed in numerical models of spontaneous gravitational clumping in a shearing disk. If this wake-dominated picture of the rings is correct, then the variation of transmission with opening angle is likely to deviate from the classical expression, T=e^{-$\tau^{\sin}$ *B*}, where τ is the normal optical depth and *B* is the ring opening angle. This expectation is confirmed by recent analyses of both UVIS (Colwell etal. 2007) and VIMS (Hedman etal. 2007) stellar occultation data.

By comparing several occultations whose lines of sight are quasi-parallel to the wakes, we can exploit this apparent variation of τ with *B* to separate the filling fraction of the wakes, *f*, from the optical depth in the `gaps' between them. We find remarkably consistent results from occultations at 11 °<*B*<51 ° spanning both the A and B rings. The most striking result is that, with the exception of the Cassini Division, where wakes appear to be absent, τ_{gap} is relatively constant over large regions of the rings and even between the A and B rings. With minor exceptions, we find that $0.15<\tau_{gap}<0.30$ everywhere wakes exist. In the B ring we find that almost all of the observed variation in optical depth with radius is due to variations in *f*. We suggest, based on numerical models of inelastic, self-gravitating particles (Salo & Karjalainen 2003), that the larger ring particles are essentially confined to narrow, dense wakes, while the gaps are filled by an extended, relatively homogeneous `haze' of somewhat smaller particles which envelops the wakes.

This work was supported by NASA via the Cassini-Huygens Project.

18.02 Edge-Waves in Ring Gaps and the Determination of Masses of Embedded Satellites

John W. Weiss[1], C. C. Porco[1], M. S. Tiscareno[2]
[1]Space Sciences Institute, [2]Cornell University.

Moons embedded in planetary-ring gaps generate radial waves on the gap-edges. The scale and morphology of these waves can be used to deduce properties of the moons, particularly their masses. However, existing analytic theory describing the relationship between the moon's mass and the edge-wave amplitudes neglects non-linear effects during encounters as well as possible effects of pre-encounter inclinations and eccentricities of the moon and particles. We will present our numerical integrations of ring-satellite encounters in which we explore the effects of the non-linearity, eccentricities, and inclinations.

We find that in the Saturnian system, Pan's mass can accurately be deduced using the existing analytic theory. Daphnis is more dynamically interesting, being more inclined, more eccentric, and closer to its gap-edge than Pan. The proximity of Daphnis to the Keeler gap's edges results in significant non-linear effects, leading to the analytic calculation over-estimating the mass of Daphnis by 30%.

The eccentricity and inclination both cause time-variable structure on the gap-edge, meaning single observations are not sufficient for determining the mass of the satellite. Additionally, Daphnis' inclination induces an inclination in

the gap-edge which conversely act to decrease Daphnis' inclination with a damping timescale of several thousands of years.

18.03 **Kinematics of the Outer Edges of Saturn's A and B Rings**

Joseph N. Spitale[1], C. C. Porco[1], J. E. Colwell[2], J. M. Hahn[3]
[1]CICLOPS/Space Science Institute, [2]Univ. of Central Florida, [3]Space Science Institute.

The outer edges of Saturn's A and B rings have long been known to possess non-axisymmetric shapes as a result of their proximity to inner Lindblad resonances with the Janus/Epimetheus system, and with Mimas, respectively (Porco et al. 1984). Using a large data set consisting of Cassini ISS imaging and UVIS occultation data, we re-examine the kinematics of these edges with much finer temporal and azimuthal resolution than previously possible. The A-ring outer edge shows the seven-lobed shape resulting from the resonance with Janus and Epimetheus, except at times within a few months of their orbital swap. The best-fitting 7-lobed mode precesses at a speed close to the raw mean of the satellites' orbital speeds, rather than the mass-weighted mean. The outer edge of the B ring displays the expected 2-lobed pattern forced by the resonance with Mimas, but unexplained additional large-amplitude, time-dependent components are present as well. Results of this kinematic modeling are used as inputs to a dynamical simulation to infer physical properties of the rings (Hahn et al., this conference).

BREAK

18.04 **The Physics of the Sharp Edges of Broad Planetary Rings**

Joseph M. Hahn[1], J. N. Spitale[2], C. C. Porco[2]
[1]Space Science Institute, [2]CICLOPS/SSI.

The outer edge of Saturn's main B ring is maintained by an m=2 inner Lindblad resonance (ILR) with the satellite Mimas, while the outer edge of Saturn's A ring is preserved by an m=7 ILR with the Janus/Epimetheus coorbital pair. These satellites' resonant perturbations excite an m-lobed disturbance at a ring's edge whose amplitude, we find, is quite sensitive to the ring's physical properties, namely, its surface density and the pressure that is a consequence of collisions among ring particles. In order to better understand these perturbed ring-edges, we have developed a nonlinear model of these resonant ring-satellite interactions, one that also accounts for the ring's internal forces, namely, ring self-gravity, pressure, and viscosity. This talk will assess the relative importance of these internal forces, and will illustrate how the ring's radial excursions and surface density variations all depend on the rings' properties. This model can then be used to diagnose the physical properties of Saturn's main rings by comparing Cassini observations to simulations of these ring edges (Spitale et al., this conference).

18.05 **Density Waves in Saturn's Rings: Non-linear Dispersion and Moon Libration Effects**

Miodrag Sremcevic[1], G. R. Stewart[1], N. Albers[1], J. E. Colwell[2], L. W. Esposito[1]
[1]LASP, Univ. Of Colorado, Boulder, [2]University of Central Florida.

We analyze strong spiral density waves in stellar occultations by Saturn's A ring observed with the Cassini Ultraviolet Imaging Spectrograph (UVIS) and find that waves dispersion relation exhibits a clear deviation from the linear trend. All waves examined here reveal an intrinsic quadratic radial dependence on the wavenumber. We provide evidence that the deviation from the linear trend is caused by the ring's pressure term acting against the self-gravity of the ring particles. From the observed dispersion relation and using the theory of Goldreich and Tremaine (1978, 1979, ApJ) where the pressure is parameterized as $p=\sigma c^2$, we measure the velocity dispersion c=2-5 mm/s in the A ring.

Additionally, in all first order Pandora waves the dispersion relation exhibits a wiggly structure. Comparing 60 stellar UVIS occultations between 2004 and 2008 we infer that this wavenumber oscillation propagates away from the resonance location with a period of about 600 days. This inferred period is consistent with the 3:2 near corotation resonance between Pandora and Mimas (French et al., 2003, Icarus). The observed libration in wavenumber allows us to accurately measure the group velocity in the rings and obtain independent estimates of both surface density and velocity dispersion of the rings.

18.06 Temporally Modulated Density Waves in Saturn's Rings

Glen R. Stewart[1], M. Sremcevic[1]
[1]Univ. of Colorado.

The standard theory of density waves in planetary rings assumes that the orbit of the perturbing satellite is on a fixed orbit. However, resonant interactions between the moons of Saturn produce significant time-dependent variations in the orbital elements of the smaller satellites. Pandora, for example, is resonantly perturbed by Mimas and therefore exhibits a 1.4 km amplitude variation in its semimajor axis with an average period of 612 days (French et al. 2003, Icarus 162: 143). We will present a variational principle for slow, time-dependent modulations of linear density waves. The resulting wave equation describes how slow oscillations in the semimajor axis of the perturbing satellite produce temporal modulations that propagate with the local group velocity of the density wave. The amplitude of the modulations depends on the ratio of the fractional variation of the satellite's semimajor axis to the frequency of the variations. For the case of the Pandora 6:5 inner Lindblad resonance, the modulation is predicted to have an amplitude of about 5%, which agrees with observations reported by Miodrag Sremcevic at this meeting. These temporal modulations provide an important alternative method for measuring the group velocity, and hence the surface mass density, in density waves observed in Saturn's rings.

18.07 Formation of Saturn's Rings by Tidal Disruption of a Centaur

Henry C. (Luke) Dones[1], C. B. Agnor[2], E. Asphaug[3]
[1]Southwest Research Institute, [2]Queen Mary, University of London, UK, [3]UCSC.

Planetary rings owe their existence to tidal forces, which frustrate accretion into larger bodies. Models for ring origin include (a) formation in situ, (b) disruption of a moon by cometary impact, and (c) tidal disruption of an interloping Centaur ([1]). [2] applied model (c) to Saturn's rings, basing his results on analytic expressions and taking Chiron to be a typical Saturn-crosser. Many Saturn-crossers have now been discovered, and our understanding of tidal disruption has advanced, particularly through models of the breakup of Comet Shoemaker-Levy 9 (SL9). [3] treated SL9 as a rubble pile, and modeled its disruption with a fast N-body code that included self-gravity and a simple model of collisions. We are using a modified version of this code to follow the tidal disruption of model Centaurs that pass within Saturn's Roche radius. Our simulations have four free parameters: the Centaur's approach velocity to Saturn (v), closest approach distance to Saturn (q), size (r), and rotation state. Mass capture is favored for events with small v and q, large r, and fast direct rotation ([4]). We will estimate the rate of ring formation by tidal disruption, and will constrain the heliocentric orbits of plausible ring parent bodies. Saturn's B Ring may be much more massive than was previously thought ([5],[6]). We will discuss the implications of a more massive ring system for different origin scenarios. We thank the NASA PGG program for support.

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