American Astronomical Society
Division on Dynamical Astronomy

34th Annual Meeting, May 4-7, 2003
Cornell University, Ithaca, NY

PROGRAM

Sunday, May 4

4:30 p.m. – 6:30 p.m.	DDA Committee Meeting, 622 Space Sciences Building
7:00 p.m. – 10:00 p.m.	Reception, Statler Hotel, Yale/Princeton Rooms
7:00 p.m. – 10:00 p.m.	Registration, Statler Hotel

Monday, May 5

8:00 a.m.	Registration, Statler Hotel Continental Breakfast—2nd Floor, Ampitheater Foyer
8:30 a.m.	Opening Remarks

Session 1: Asteroids—Chaired by *J. Burns*

8:40 a.m.	(1.01)	Asteroids: Radar Observations and Dynamics *S. J. Ostro* (**Invited**)
9:30 a.m.	(1.02)	Morphological Evolution of Asteroids *D. C. Richardson* (**Invited**)
10:20 a.m.		**Coffee Break**—Ampitheater Foyer

Session 2: Small Bodies—Chaired by *J. Hilton*

10:40 a.m.	(2.01)	Measuring the Yarkovsky Effect via Radar Ranging to Golevka: Place Your Bets *S. R. Chesley, D. Vokrouhlický, D. Capek, S. J. Ostro*
10:55 a.m.	(2.02)	The Dynamical Environment of Binary Asteroids *D. J. Scheeres*
11:10 a.m.	(2.03)	Rotational Dynamics of a Deformable Symmetric Ellipsoid *I. Sharma, J. T. Jenkins, and J. A. Burns*
11:25 a.m.	(2.04)	The Impact Frequency of Near-Earth Asteroids *A. W. Harris*
11:40 a.m.	(2.05)	The Decoupling of Jupiter-Family Comets *S. I. Ipatov, J. C. Mather*
11:55 a.m.	(2.06)	The Dynamics of Known Centaurs *M. S. Tiscareno and R. Malhotra*
12:10 a.m.		**Lunch**

Session 3: Galactic Dynamics—Chaired by *F. Adams*

1:15 p.m.	(3.01)	Making Sense of the GAIA Catalogue J. J. Binney (**Brouwer Award Lecture**)
2:05 p.m.	(3.02)	Stellar and Gas Dynamics in the Central Parsec of the Galaxy *M. Morris* (**Invited**)

2:55 p.m.	(3.03)	Kinematics of the Galactic Halo Using Blue Horizontal Branch Stars Selected from the Sloan Digital Sky Survey *E. Sirko* (**Student Stipend Recipient**), *G. R. Knapp, J. Goodman, D. J. Schlegel, and E. J. Knerr*
3:10 p.m.	(3.04)	Disk-Crossing Orbits *C. Hunter*
3:25 p.m.	(3.05)	NGC4365: A Truly Triaxial Galaxy *T. S. Statler, SAURON Team*
3:40 p.m.	(3.06)	Local Surface Density of the Galactic Disk *V. I. Korchagin, T. M. Girard, T. V. Borkova, D. I. Dinescu, W. F. van Altena*
3:55 p.m.		**Coffee Break**—Ampitheater Foyer

Session 4: Energetic Dynamics—Chaired by *D. J. Scheeres*

4:15 p.m.	(4.01)	Numerical Simulations of Black Holes *S. Teukolsky* (**Invited**)
5:05 p.m.	(4.02)	A Capture Scenario for Globular Cluster Omega Centauri *T. Tsuchiya, D. I. Dinescu, and V. I. Korchagin*
5:20 p.m.	(4.03)	Stability of Surface Motion on Rotating Ellipsoids *V. M. Guibout and D. J. Scheeres*
5:35 p.m.		**Dinner**

Session 5: Business Meeting

7:00 p.m.—8:00 p.m.

Session 6: Poster Papers—Chaired by *H. F. Levison*

8:00 p.m.	(6.01)	First Results from AGK2 Plate Measurements *N. Zacharias, S. E. Urban, T. J. Rafferty, and L. Winter*
	(6.02)	Constraints on Spiral Modes Propagating in the Solar Neighborhood *A. Quillen*
	(6.03)	Efficient Orbit Integration by Scaling for Kepler Energy Consistency *T. Fukushima*
	(6.04)	A Method of Non-linear Harmonic Analysis and its Application to Determination of Planetary Precession in DE405 *T. Fukushima and W. Harada*
	(6.05)	The Gravity Field of the Saturnian System *R. A. Jacobson*
	(6.06)	Migration of Asteroidal Dust Particles *S. I. Ipatov, J. C. Mather, and P. A. Taylor*
	(6.07)	HST Astrometry of Saturn's Small Satellites *R. G. French and C. A. McGhee*
	(6.08)	Three-Dimensional Simulations of High and Low-Mass Planets Embedded in Protoplanetary Disks *S. H. Lubow, M. R. Bate, G. I. Ogilvie, and K. A. Miller*

	(6.09)	Lunar and Artificial Satellite Laser Ranging: The Use of Queue Scheduling and Worth Functions to Maximize Scientific Results *P. J. Shelus, R. L. Ricklefs, J. R. Wiant, and J. G. Ries*
	(6.10)	Coupled Orbital-Rotational-Tidal Dynamics of Io *S. Musotto, F. Varadi, W. Moore, and G. Schubert*
	(6.11)	Resonant Periodic Orbits in Elliptic Three-Body Systems *J. Couetdic, N. Highighipour, F. Varadi, and W. B. Moore*
	(6.12)	Getting Physical: Rotation Rate Determination for PHAs *J. G. Ries, E. S. Barker, P. J. Shelus, R. L. Ricklefs*
	(6.13)	Candidate Asteroids for Discerning General Relativity and Solar Oblateness *J. L. Margot*
	(6.14)	On an Analytical Solution for the Minimum Distance Between Two Confocal Elliptical Orbits Used as a Close Approach Filter *M. A. Murison and A. Munteanu*
	(6.15)	A Search for Asteroids on Earth Horseshoe Orbits *J. L. Margot and P. D. Nicholson*
	(6.16)	The Distribution in Eccentricity and Inclination, as a Function of the Semi-Major Axis of Asteroids *H. Varvoglis and S. Koukioglou*
	(6.17)	Cutoff energy Behavior for an Ideal Gas *M. Cahill*

Tuesday, May 6

Continental Breakfast—Ampitheater Foyer

Session 7: Space Missions, Astrometry, and Observables

—Chaired by *P. D. Nicholson*

8:30 a.m.	(7.01)	The GRACE Mission: Status and Early Results *B. D. Tapley, C. Reigber, and J. C. Ries* (**Invited**)
9:20 a.m.	(7.02)	The Yale/San Juan Southern Proper Motion Catalog 3.0 *T. M. Girard, D. I. Dinescu, W. F. van Altena, I. Platais, C. E. Lopez, and D. G. Monet*
9:35 a.m.	(7.03)	A Comparison of Large All-Sky Catalogs to the Sky *D. J. Mink, W. R. Brown, and M. J. Kurtz*
9:50 a.m.	(7.04)	Schlesinger's Telescope: A Brief History of the Yale 26-Inch Refractor *W. F. van Altena and E. D. Hoffleit*
10:05 a.m.	(7.05)	New Precession Formula *T. Fukushima*
10:20 p.m.	(7.06)	A Nonlinear Model for the Relative Motion of Satellites *K. T. Alfriend and H. Yan*
10:35 p.m.	(7.07)	The Mass Ratio of Charon to Pluto from Hubble Space Telescope Astrometry with the Fine Guidance Sensors *C. B. Olkin, L. H. Wasserman, and O. G. Franz*

10:50 a.m.		**Coffee Break**—Ampitheater Foyer

Session 8: Extra-Solar Planetary Systems—Chaired by *R. G. French*

11:10 a.m.	(8.01)	Planet Scattering and Exoplanet Orbits *R. K. Barnes* (**Student Stipend Recipient**), *and T. R. Quinn*
11:25 a.m.	(8.02)	Obliquity Variations of Terrestrial Planets in Habitable Zones *K. Atobe and T. Ito*
11:40 a.m.	(8.03)	Dynamical Models of the Planets Orbiting the Star GJ 876 Subject to Doppler and Astrometric Constraints *E. J. Rivera and J. J. Lissauer*
11:55 a.m.		**Lunch**

Session 9: Standards and Gauges—Chaired by *D. Merritt*

1:00 p.m.	(9.01)	The IAU2000 Standards: The Newly Adopted Time, Coordinates, and Reference Frames *E. M. Standish* (**Invited**)
1:50 p.m.	(9.02)	The Method of variation of constants and Multiple Time Scales in Orbital Mechanics *W. I. Newman and M. Efroimsky*
2:05 p.m.	(9.03)	Gauge-Invariant Disturbing Function in Precessing Frames of Reference *M. Efroimsky and P. Goldreich*
2:20 p.m.	(9.04)	Gauge Drift in Numerical Integrations of the Lagrange Planetary Equations *M. A. Murison and M. Efroimsky*
2:35 p.m.	(9.05)	Satellite Orbit Plane Perturbations Using an Efroimsky Gauge Velocity *V. J. Slabinski*
2:50 p.m.	(9.06)	Adventures in Coordinate Space *J. E. Chambers*
3:05 p.m.		**Coffee Break**—Ampitheater Foyer

Session 10: Satellites and Rings—Chaired by *L. Aguilar*

3:25 p.m.	(10.01)	Kozai Resonators among Distant Moons of the Jovian Planets *V. Carruba, D. Nesvorny, J. A. Burns, and M. Cuk*
3:40 p.m.	(10.02)	Consequences of the Chaotic Motions of Prometheus and Pandora *S. Renner and B. Sicardy*
3:55 p.m.	(10.03)	On the Problem of Phoebe's Family *M. Cuk, J. A. Burns, D. Nesvorny, B. J. Gladman, and V. Carruba*

4:10 p.m.	(10.04)	An Instability in Narrow Planetary Rings *J. W. Weiss and G. R. Stewart*
4:25 p.m.	(10.05)	Effect of Slow Variations of Parameters for 2 Co-Orbital Satellites and Stationary Configurations for N Co-Orbital Satellites *B. Sicardy, S. Renner, and V. Dubois*
4:40 p.m.	(10.06)	New Problems and Theories of Synchronous Rotation *F. Varadi, S. Musotto, W. Moore, and G. Schubert*
4:55 p.m.	(10.07)	Limits on Inclinations in Saturn's Rings *A. S. Bosh*
6:00 p.m.—10:00 p.m.		**Banquet** at Taughannock Farms Inn Buses will leave Statler at 5:30 and 6:30 p.m.; hike at 6:00 p.m. beginning at Taughannock State Park

Wednesday, May 7

Continental Breakfast—Ampitheater Foyer

Session 11: Disks—Chaired by *S. Howard*

8:30 a.m.	(11.01)	Formation of Terrestrial Planets in a Dissipating Gas Disk with Jupiter and Saturn *J. Kominami and S. Ida*
8:45 a.m.	(11.02)	Constraints on the Size of the Circumplanetary Gas Disk *I. Mosqueira and P. R. Estrada*
9:00 a.m.	(11.03)	Gas Drag Induced Enhancement of the Growth-Rate of Planetesimals *N. Haghighipour*
9:15 a.m.	(11.04)	Viscous Evolution of an Impact Generated Water/Rock Disk Around Uranus *W. R. Ward and R. M. Canup*
9:30 a.m.	(11.05)	Gas Drag Effects on the Orbital Evolution of Classical Edgeworth-Kuiper Belt Objects After an Early Stellar Encounter *H. Kobayashi, S. Ida, and H. Tanaka*
9:45 a.m.	(11.06)	Instabilities of Stellar Disks *M. A. Jalali and C. Hunter*
10:00 a.m.	(11.07)	Saturation of the Corotation Resonance in a Gaseous Disk *S. H. Lubow and G. I. Ogilvie*
10:15 p.m.	(11.08)	The Secular Evolution of the Primordial Kuiper Belt *J. M. Hahn*
10:30 a.m.		**Coffee Break**—Ampitheater Foyer

Session 12: Migration and Others—Chaired by *A. Fiala*

10:50 a.m.	(12.01)	Migration and Dynamical Relaxation in Crowded Systems of Giant Planets *F. C. Adams*
11:05 a.m.	(12.02)	Planetary Growth: From the Gap-opening Mass to the

		Final Mass of the Giant Planet *P. R. Estrada and I. Mosqueira*
11:20 a.m.	(12.03)	Resonant Inclination Excitation of Migrating Giant Planets *E. W. Thommes and J. J. Lissauer*
11:35 a.m.	(12.04)	Pushing Out the 'Cold' Classical Kuiper Belt *H. F. Levison and A. Morbidelli*
11:50 a.m.	(12.05)	On the Origin of the Laplace Relation Among the Galilean Satellites *S. J. Peale and M. H. Lee*
12:05 p.m.	(12.06)	Diversity and Origin of 2:1 Orbital Resonances in Extrasolar Planetary Systems *M. H. Lee and S. J. Peale*
12:20 p.m.	(12.07)	Restricted Three-Body Dynamics and Morphologies of Early Nova Shells and Their Spectral Signatures *D. K. Lynch, S. Mazuk, E. Campbell, and C. C. Venturini*
12:35 p.m.		**Adjourn**

Abstracts

[1.01] Asteroids: Radar Observations and Dynamics

S. J. Ostro (*JPL/Caltech*)

Radar delay-Doppler measurements are powerful for refining asteroid orbits because they have extremely fine fractional precision and are orthogonal to optical angle astrometry. Radar detection of a newly discovered near-Earth asteroid (NEA) secures its orbit and can add centuries to the interval over which its close Earth approaches can accurately be predicted. With radar, refinement of orbits is so tightly coupled to physical characterization that almost every asteroid radar experiment that produces new information about a target's size, shape, rotation, and surface properties also furnishes astrometry for improving the ephemerides.

Delay-Doppler images of NEAs can achieve decameter resolution. Models derived from image sequences let one explore the evolution and stability of close orbits, with direct application to navigation of spacecraft and to investigation of impact-induced regolith redistribution. Radar signatures have been measured for more than 200 asteroids whose size and spin-period distributions span four orders of magnitude. Radar can reveal excited rotation states, contact-binary shapes, and binary systems, and has identified several NEAs in each of those categories. The radar binaries are yielding our first accurate estimates of the masses and densities of potentially hazardous asteroids.

Bibliography: Benner et al. (2002), Meteoritics Planet. Sci. 37-51, 779. Giorgini et al. (2002), Science 296, 132-136. Hudson et al. (2003), Icarus 161, 348-357. Magri et al. (2001), Meteoritics Planet. Sci. 36, 1697-1709. Margot et al. (2002), Science 296, 1445-1448. Nolan et al. (2002), IAU Circ. No. 7921. Ostro et al. (2002), in Asteroids III, ed. Bottke et al., U. Arizona, pp. 151-168. Scheeres et al. (1998), Icarus 132, 53-79. Vokrouhlicky et al. (2001), Cel. Mech. Dyn. Astron. 81, 149-165.

[1.02] Morphological Evolution of Asteroids

D. C. Richardson (*University of Maryland*)

Recent ground- and space-based observations of asteroids have revealed that these bodies are far more complex than once imagined. Surprisingly low bulk densities, giant craters, unusual shapes, non-principal-axis spin states, and satellites are all challenging our understanding of how asteroids form and evolve. Since asteroids are the remnants of the planet building era, understanding their nature improves our understanding of the origin of solar systems in general. I will review some of the more puzzling aspects of asteroid morphology, including the existence of asteroid satellites, and discuss recent theoretical advances aimed at understanding our tiny neighbors. I will show that both theoretical and observational evidence is pointing increasingly to asteroids being fragile assemblages of smaller pieces, called gravitational aggregates. The consequences of such fragmented internal structure on asteroid evolution and hazard mitigation will be discussed. This work has been supported in part by the National Aeronautics and Space Administration under Contract No. NAG511722 issued through the Office of Space Science.

[2.01] Measuring the Yarkovsky Effect via Radar Ranging to Golevka: Place Your Bets

S. R. Chesley (*JPL*), D. Vokrouhlický, D. Capek (*Charles Univ., Prague*), and S. J. Ostro (*JPL*)

The Yarkovsky effect, a subtle nongravitational phenomenon involving accelerations of an object due to anisotropic thermal emission of absorbed sunlight, has been invoked to explain the transport of asteroids into the inner solar system, as a source mechanism for meteorites, as one of the processes that affect the evolution of asteroid spin states, and a factor that limits the long-term predictability of near-Earth asteroid trajectories. However, despite its profound theoretical importance in asteroid science, Yarkovsky accelerations have never been detected in the motion of natural objects in the solar system. Vokrouhlicky et al. [Icarus 148, 118-138 (2000)] have argued that precise radar refinement of the orbits of near-Earth asteroids offers the possibility of detecting the Yarkovsky effect during the next few decades.

We will describe prospects for detection of the Yarkovsky effect from fine-precision delay-Doppler radar observations of the half-kilometer asteroid 6489 Golevka in late May 2003. This "test" of the effect will make use of a previously published, radar-derived physical model of the asteroid as well as one of the most sophisticated Yarkovsky models implemented to date. The Yarkovsky acceleration depends strongly on the asteroid's bulk density and surface thermal conductivity. We will discuss the extent to which the radar astrometry should be able to constrain these physical properties. Predictions of the outcome of the experiment will be solicited from the audience.

[2.02] The Dynamical Environment of Binary Asteroids

D. J. Scheeres (*University of Michigan*)

Particle motion about asteroid binaries is a topic of interest for understanding ejecta dynamics in binary systems, transient dynamics following formation of a binary system, and for the motion of spacecraft in the vicinity of binary asteroids. The problem, in its most general form, is difficult and requires modeling of the non-spherical mass distributions of the bodies, the mutual orbital and rotational motion of the bodies, and the perturbative influence of the sun on the system. Particle motion in these systems can be very complex, and may consist of orbits bound to either of the asteroid bodies, exchange trajectories between the bodies and with the exterior region, and orbits isolated in the exterior region about both bodies.

When properly formulated, the binary environment integrates 4 classical problems of celestial mechanics into a single environment: the Hill problem, the restricted 3-body problem, the non-spherical orbiter problem, and the full 2-body problem. In this talk we focus on the effect of the solar perturbation, and show how this creates an environment that modifies the restricted 3-body problem and leads to instability for particle motion over a wide range of parameter space. In particular, we find a simple parameter condition for stability in the vicinity of the triangular libration points. $\frac{T_o}{T_h} < \frac{27}{8}m(1-m) < \frac{1}{8}$ where T_o is the orbital period of the binary system, T_h is the orbital period of the binary system about the sun, and m is the mass distribution parameter for the binary system. The upper limit of the inequality is the familiar result from the restricted 3-body problem and limits the stability of bodies with similar masses. The lower limit of the inequality arises from the solar perturbation, and preferentially limits the stability of small mass fraction systems. Thus, resulting from this inequality (which specifically applies only to systems with zero obliquity) we expect most asteroid binaries that fall into this class to have complete instability in all their synchronous motions. Conversely, if the asteroid system has a relative inclination of 180 degrees, the lower limit disappears, reducing to the more familiar unperturbed case.

This research is supported in part by NASA's Office of Space Science Planetary Geology and Geophysics Program.

[2.03] Rotational Dynamics of a Deformable Symmetric Ellipsoid

I. Sharma, J. T. Jenkins, and J. A. Burns (*Dept. of Theoretical and Applied Mechanics, Cornell University*)

As a first step towards following the rotational evolution of wobbling asteroids we consider the rotational dynamics of deformable ellipsoids. In general, a full set of balance equations need to be solved. However, it's difficult to obtain analytical or numerical solutions to these for general constitutive laws. Even in the case of a linear elastic body, where analytical solutions are available (assuming quasi-statics), the solutions are much too unwieldy. One way to reduce the problem's complexity and still include the effects of elasticity, viscosity, and/or friction is to successively approximate the deformation in terms of its linear (homogeneous), quadratic, cubic, etc. parts. This can be done very systematically via the virial method (Chandrasekhar S., 1969). The advantage of this method is that it allows us to investigate a wide variety of constitutive laws, include the effects of internal gravity and external force fields, and make better estimates of the amount of internal energy dissipated. To demonstrate the method, we present analytical solutions obtained for the case of an axi-symmetric, linearly elastic ellipsoid executing free Eulerian motion.

[2.04] The Impact Frequency of Near-Earth Asteroids

A. W. Harris (*Space Science Inst.*)

The impact probability of a given asteroid with the Earth depends strongly on the details of its orbit, i.e. orbits which intersect the Earth's orbit at low inclination or nearly tangent at perihelion or aphelion have much higher impact probabilities than more steeply crossing orbits. Since the Earth may clear out objects in such orbits faster than they are supplied, the actual distribution of such orbits may be highly non-random, and thus the collision frequency from the actual equilibrium population is difficult to model theoretically. I have taken a direct approach to estimating the current impact flux by using the sample of all discovered NEAs with absolute magnitude less than 18.0 (approximately 1 km in diameter or larger). This provides a large enough sample, more than 600 objects, to provide good statistics of impact frequency, and yet is relatively unbiased since it is expected to be more than half complete of all existing NEAs that large. Of this sample, approximately half are Earth-crossing asteroids (have perihelia less than 1.0 AU and thus can impact the Earth at some time in the normal precessional cycle of their orbits. I compute the circumstances of passages of all these objects within 0.1 AU of the Earth over a period of one century (in the future to remove any bias from the discovery apparition). The frequency of passages within 0.1 AU can be easily scaled to obtain the frequency of passages within the Earth's radius, with allowance for gravitational focusing, and thereby obtain an estimate of the impact frequency of the actual observed population of NEAs. The result is that the "per object" impact frequency of all NEAs (q ¡ 1.3 AU) is 1.7 x 10^{-9} y^{-1}. An associated result is the RMS impact velocity, which is about 20 km/sec.

This research will hopefully be funded by the Planetary Geology and Geophysics Program of NASA, when 2003 funding finally gets released.

[2.05] Decoupling of Jupiter-Family Comets

S. I. Ipatov (*NRC/NAS Senior Research Associate, NASA/GSFC; Inst. Appl. Math., Moscow;* siipatov@hotmail.com) and J. C. Mather (*NASA/GSFC*)

The orbital evolution of about 8000 and 5400 objects with initial orbits close to those of Jupiter-family comets (JFCs) was integrated with the use of the Bulirsh-Stoer and symplectic methods, respectively. The gravitational influence of planets (except for Pluto, and sometimes Mercury) was taken into account. In the case of close encounters with the Sun (e.g., for Comet Encke 2P) the probability of collisions with the Sun was different for different methods and different accuracy per integration step, but all other obtained results were similar. Decoupling from Jupiter was found for less than 1% of the simulated JFCs. About 0.1% of the migrating studied JFCs reached orbits with a semi-major axis $a < 2$ AU for more than 0.5 Myr. Several former JFCs moved in such orbits for tens or even hundreds of Myrs, and even reached Aten orbits and inner-Earth orbits, which are located inside the orbit of the Earth. Based on orbital elements sampled with a 500 yr step, we calculated the mean probabilities of collisions of objects with planets. If we exclude a few bodies with the largest probabilities, the mean probability 'P' of a collision of a former JFC with the Earth during the lifetime of the object was about $4*10^{-6}$, enough for delivering an amount of water similar to the mass of Earth oceans during the formation of the giant planets. For some runs this probability was smaller (the same as that obtained by other scientists, who considered relatively small number of objects and did not obtain decoupling from Jupiter), but a few objects increased the above mean value of 'P' by more than an order of magnitude. The probability of a collision with Earth or Venus for a single former JFC moving in a typical orbit of a near-Earth object (NEO) for millions of years could be greater than the total for thousands of other objects. Based on the runs of orbital evolution of JFCs and using the results of migration of trans-Neptunian objects to the orbit of Jupiter, we concluded that up to several tens of percent of NEOs could be extinct comets that came from the trans-Neptunian region. Some former comets that have moved in typical NEO orbits for millions or even hundreds of millions of years, and might have had multiple close encounters with the Sun, could have lost their mantles, which caused their low albedo, and so change their albedo and would look like typical asteroids. Several our papers on this problem were put in http://arXiv.org/format/astro-ph/, the last one is astro-ph/0303219.
This work was supported by NRC (0158730), NASA (NAG5-10776), INTAS (00-240), and RFBR (01-02-17540).

[2.06] The Dynamics of Known Centaurs

M. S. Tiscareno and R. Malhotra (*U of Arizona*)

We have numerically investigated the long term dynamical behavior of known Centaurs. This class of objects is thought to constitute the transitional population between the Kuiper Belt and the Jupiter-family comets (JFCs). In our study, we find that this transient population diffuses into the JFCs and other sinks, but (not surprisingly) does not diffuse back into the parameter space representing the presumed Kuiper Belt source. Their orbital evolution is characterized by frequent close encounters with the giant planets. Most of these Centaurs will escape from the solar system (or enter the Oort Cloud), while a fraction will enter the JFC population and a few percent will impact a giant planet.

Their median dynamical lifetime is 9 Myr, although there is a wide dispersion in lifetimes, ranging from less than 1 Myr to more than 100 Myr. We find the dynamical evolution of this sample of Centaurs to be less orderly than the planet-to-planet "hand-off" described in previous investigations. Based on our simulations, and assuming a steady-state population, we estimate the spatial distribution of Centaurs: their surface density increases steeply from $r = 5$ AU to about $r = 15$ AU, is nearly constant from $r = 15$ AU to $r = 30$ AU, peaks near 30 AU, and decreases thereafter approximately as a power law, $\sim r^{-2.5}$, where r is heliocentric distance.

MST is supported by a National Science Foundation Graduate Research Fellowship. RM acknowledges NASA for research support.

[3.01] Making Sense of the GAIA Catalogue

J. J. Binney (*Oxford University*)

In the 5 years from 2011 ESA's GAIA mission will conduct the first magnitude-limited astrometric survey of the whole sky. It will measure coordinates for about 10^9 stars to $V \sim 20$. In the GAIA catalogue, stars brighter than $V \sim 15$ will have parallaxes accurate to 10% out to distances $R \sim 10\,\mathrm{kpc}$. Stars brighter than $V \sim 17$ will have radial velocities good to a few $\mathrm{km\,s^{-1}}$. An elaborate series of intermediate-band colours will be measured for all stars.

I will argue that to exploit this spectacular catalogue effectively, it will be necessary to construct around it a dynamical model of the Galaxy. The model will have to be constructed iteratively and exploit techniques from solar-system dynamics much more extensively than is usual in galactic astronomy. Thus the GAIA mission challenges us to break new ground in galactic dynamics.

[3.02] Stellar and Gas Dynamics in the Central Parsec of the Galaxy

M. Morris (*UCLA*)

With a radius of about 1.5 pc, the domain of influence of the supermassive black hole at the center of our Galaxy, which has a radius of about 1.5 pc, is a phenomenologically rich region about which much can be learned from the dynamics of both stars and gas. The radial distribution of the relatively old stars in the central stellar cluster, as well as its core radius, are determined from imaging studies, while statistical analyses of radial velocities and proper motions provide a determination of the enclosed mass. However, the presence of an apparent hole in the red giant distribution has a strong effect on the statistical mass estimations. The early-type stellar population in the central parsec is quite a different matter. First, there is the paradox of how apparently young stars can be present in the region in which the tidal forces of the black hole should have suppressed normal star formation. Potential solutions to this paradox will be discussed, with particular attention paid to whether dynamical friction can cause stars to migrate inwards on a sufficiently short time scale. Second, the dynamics of early-type stars in the central arcsecond (0.04 pc) have lately been providing a great deal of information on the neighborhood of the central black hole. A decade of proper motion studies, combined with recent spectroscopy, now reveal almost complete orbits of some of the stars closest to the central black hole. These orbits yield the black hole mass, its location (to within 1.5 milliarcsec), and a limit on its proper motion. Limits on the orbital precession and on the variation of central mass with periapse distance constrain the extended mass distribution, hypothetically in the form of stellar remnants or dark matter particles (relativistic precession is even less accessible). In

fitting orbits simultaneously to the plane-of-sky motions and radial velocities, one additional parameter which can be fit is the Galactic center distance, D. Now consistent with other determinations, the value of D inferred in this way should soon become the most accurate measure available. Gas motion, which can be affected by non-gravitational forces, provides a complementary probe of the central parsec. Several gas streams have been identified, and their dynamics studied, also using both spectroscopic and proper motion measures. A few of these streams – the Northern and Eastern Arms – appear to be infalling on predominantly radial orbits. The details of the Northern Arm dynamics, as determined using imaging spectroscopy by Paumard et al. (2003) will be presented. Because it is likely to self-intersect and form a dispersion ring, this feature will presumably lead to a significant accretion episode on a time scale of a few times 10^4 years, as the gas encounters the black hole.

[3.03] Kinematics of the Galactic Halo Using Blue Horizontal Branch Stars Selected from the Sloan Digital Sky Survey

E. Sirko, G. R. Knapp, J. Goodman, D. J. Schlegel, and E. J. Knerr (*Princeton University Observatory*)

A sample of ~ 1000 Galactic halo blue horizontal branch (BHB) stars is drawn from the Sloan Digital Sky Survey (SDSS) spectroscopic database. Preliminary cuts in $(u^* - g^*, g^* - r^*)$ distinguish candidate BHBs, which have a strong Balmer jump, from other halo stars. Surface-gravity indicators based on Balmer lines are further used to reject main sequence stars and blue stragglers: the $D_{0.2}$ method (linewidths at 80% of the continuum) and the scalewidth-shape method (Clewley et al. 2002). After all three cuts, contamination by non-BHB stars is estimated to be less than 10% among stars brighter than $g^* = 18$. For fainter stars the linewidth analyses are unreliable, so a more stringent $(u^* - g^*, g^* - r^*)$ cut is devised which, by comparison with the spectroscopically purified bright sample, is estimated to produce a contamination fraction of $\sim 25\%$ for $18 < g^* < 20$. Radial velocities and photometric distances are derived for the surviving stars. A maximum-likelihood method is used to determine the velocity ellipsoid of the halo. We find the velocity ellipsoid to be nearly isotropic with $(\sigma_r, \sigma_\theta, \sigma_\phi) = (99 \pm 3, 94 \pm 14, 118 \pm 18)\,\mathrm{km\,s^{-1}}$ or $(\sigma_R, \sigma_\phi, \sigma_z) = (99 \pm 8, 116 \pm 18, 99 \pm 6)\,\mathrm{km\,s^{-1}}$ in spherical and cylindrical coordinates, respectively. When the halo rotation and solar velocity are allowed to be free parameters, we also find $v_{\mathrm{halo}} = 7 \pm 18\,\mathrm{km\,s^{-1}}$ and $(U, V, W) = (13 \pm 8, 228 \pm 13, -9 \pm 5)\,\mathrm{km\,s^{-1}}$. The halo parameters are robust with respect to variations in the errors assumed: photometric distance errors up to 0.5 mag, and velocity errors up to $30\,\mathrm{km\,s^{-1}}$. Monte Carlo simulations validate the maximum likelihood technique. The conclusion that the radial component is as small as $\sim 100\,\mathrm{km\,s^{-1}}$ is firm but contrasts with many previous studies based on halo stars in the solar neighborhood.

[3.04] Disk-crossing Orbits

C. Hunter(*Florida State U.*)

This talk will discuss studies of orbits in simplified models of galaxies which consist of just two components, a disk and a halo. The disk is idealized as razor-thin, though evidence shows that this simplifying assumption is not critical. The presence of the disk causes many more resonances than have been found in similar smooth potentials. These resonances grow at relatively modest values of energy, overlap, and give rise to many stochastic orbits. A significant range of regular orbits remain and show smooth KAM curves, even though the

discontinuous potential due to the razor-thin disk means that current versions of the KAM theorem do not apply.

This work has been supported by NSF through grant DMS-0104751.

[3.05] NGC 4365: A Truly Triaxial Galaxy

T. S. Statler (*Ohio University*), SAURON Team

NGC 4365 is a photometrically ordinary, but kinematically intriguing, E2-3 galaxy. The map of the stellar mean velocity field obtained by the SAURON integral field spectrograph on the William Herschel Telescope shows that the apparent rotation axis, or zero-velocity contour (ZVC), is unaligned with the photometric axes, and that the velocity field (VF) is not symmetric about the ZVC. These traits are both expected hallmarks of non-axisymmetry. Moreover, the galaxy has a pronounced counterrotating core. We have modeled the VF and surface photometry of NGC 4365 using an approach in which the equation of continuity is solved in ellipsoidal coordinates and the resulting projected models are compared with the data by Bayesian methods to constrain the shape profile and orientation of the galaxy. We find that NGC 4365 is indeed highly triaxial, with mean axis ratios of roughly 1 : 0.8 : 0.6. Axisymmetric shapes are strongly ruled out. There is no indication of a significant change of intrinsic shape anywhere in the galaxy, including the counterrotating core. Since absorption line index measurements and the lack of photometric fine structure both indicate that NGC 4365 is at least 10 Gyr old, the dynamical results demonstrate that triaxiality in stellar systems can be long lived, and is not necessarily destroyed by orbital chaos.

[3.06] Local Surface Density of the Galactic Disk

V. I. Korchagin, T. M. Girard (*Yale University, Dept. of Astronomy*), T. V. Borkova (*Institute of Physics, Rostov University, Rostov-on-Don, Russia*), D. I. Dinescu, and W. F. van Altena (*Yale University, Dept. of Astronomy*)

Using parallaxes and proper motions of a kinematically and spatially unbiased sample of old bright red giant stars from the Hipparcos catalog with measured radial velocities from Barbier-Brossat & Figon (2000), we have re-estimated the surface density of the Galactic disk in the solar neighborhood within ± 0.4 kpc of the Sun. We determine the vertical distribution of the red giants as well as the vertical velocity dispersion of the sample, (14.4 ± 1.5 km/sec), and combine these to derive the surface density of gravitating matter in the Galactic disk, obtaining a value of 44 ± 9 M_{sun} / pc^2 within ± 400 pc. Furthermore, we find that this gravitating matter is concentrated within a layer of about ± 200 pc.

The derived values of surface density and concentration of gravitating matter indicate the presence of a thin, dark-matter component to the Galaxy. In the mid-plane of the disk, the volume density of this flattened component is a substantial fraction of the volume density of the observed matter.

This work was supported in part by grant No. AST 0098548 from the National Science Foundation.

[4.01] Numerical Simulations of Black Holes

S. A. Teukolsky (*Cornell University*)

Einstein's equations of general relativity are extremely complicated and difficult to solve. Recently great progress has been made in trying to solve these equations numerically using supercomputers. Problems involving black holes are particularly challenging. I will describe the results of recent calculations of black hole collisions, and relate the results to the current observational search for gravitational waves. Needless to say, no knowledge of general relativity will be assumed.

This work was supported in part by the National Science Foundation.

[4.02] A Capture Scenario for Globular Cluster Omega Centauri

T. Tsuchiya (*Astronomishes Rechen-Institut, Heidelberg*), D. I. Dinescu, and V. I. Korchagin (*Yale University*)

Recent advances in understanding the nature of omega Centauri - the most massive Milky Way globular cluster - have now placed on a firmer ground its accretion origin as opposed to formation within the Milky Way. Unlike the majority of the Milky Way globular clusters, omega Cen is a complex chemical system with an extended star-formation history.

We explore an accretion origin for omega Cen by N-body modeling of the orbital decay and disruption of a Milky-Way dwarf satellite. We find that a capture scenario can produce an omega Cen-like object with the current low energy orbit of the cluster. Our best model is a nucleated dwarf galaxy with a Hernquist density profile that has a mass of 8 x 10^9 $M_\odot$, and a half-mass radius pf 1.4 kpc.

This work has been supported by NSF grant AST-0098687.

[4.03] Stability of Surface Motion on Rotating Ellipsoids

V. M. Guibout and D. J. Scheeres (*University of Michigan, Aerospace Engineering Department*)

The dynamical environment on the surface of a rotating, solid ellipsoid is studied, with applications to surface motion on an asteroid. The analysis is performed using a combination of classical dynamics and geometrical analysis. Due to the small size of most asteroids, their shapes tend to differ from the spheroidal shapes found for the planets. The tri-axial ellipsoid model provides a non-trivial approximation of the gravitational potential of an asteroid and is amenable to analytical computation. Using this model, we develop the conditions for equilibrium on the surface. In general an ellipsoid will only have 6 unique equilibrium points (each symmetric about the origin), but we also find situations where every point on the surface may be in equilibrium. We also study stability of these equilibria and show that it is intimately related to the well-known families of Jacobi and MacLaurin ellipsoids. Using geometrical analysis we can define global constraints on motion as a function of shape, rotation rate, and density. We find that some asteroids should have accumulation of material at their ends, while others should have accumulation of surface material at their poles, depending on what their shape and rotation rate are in relation to the classical figures of equilibrium.

The current analysis ignores the small scale geometry of a real surface and considers frictionless dynamics. Although we use such an idealized model, this study has implications for the global trends of natural material distribution on asteroids and for the ballistic motions of an artificial vehicle close to the surface of an asteroid.

[6.01] First Results from AGK2 Plate Remeasurements

N. Zacharias, S. E. Urban, T.J. Rafferty (*USNO*), and L. Winter (*Hamburg Observatory*)

Between 1928 and 1931 the sky north of declination -5 degrees was photographed on 1940 glass plates (each covering over 5 by 5 degrees) with two dedicated astrographs (scale 100"/mm) located in Bonn and Hamburg, Germany. The resulting catalog, called "Zweiter Katalog der Astronomischen Gesellschaft", AGK2, contains about 186,000 stars. However, $\approx$ 10 times more stars are measurable on the plates.

In 2001 Hamburg Observatory loaned all AGK2 plates to the U.S. Naval Observatory (USNO) for remeasurement. The USNO StarScan machine in Washington DC started to measure those plates in early 2002; measuring should finish mid 2003. All images on all plates are digitized with a CCD camera behind a telecentric lens. The repeatability of the StarScan machine is $\approx$ 0.2 micron and measurements are believed to be accurate to 0.5 micron. Images down to $\approx$ B=12 are measured from these fine-grain emulsions.

Hipparcos stars are used for reference and preliminary positions have been obtained for over 950,000 stars from a sub-set of the plates (+20° to +55° declination). For well-exposed images, positional errors on the order of 70 mas per star coordinate are obtained. These data were used as part of the proper motion program of the second USNO CCD Astrograph Catalog release (UCAC2). Based on the AGK2 and UCAC2 positions, proper motions of 1 mas/yr are obtained, which is a factor of $\approx$ 2 better than previously best known (from AC2000-Tycho2) for stars in this magnitude range. The final AGK2 data will have significant implications for galactic kinematics and other areas of research.

[6.02] Constraints on Spiral Modes Propagating in the Solar Neighborhood

A. Quillen (*U. Rochester*)

Hipparcos has revealed a lot of structure in the solar neighborhood stellar velocity distribution. Clumps seen in blue stars are often also present in the older stars, suggesting that these clumps are not due to evaporating clusters but are due to coherent spiral modes. I will place constraints on the pattern speeds and perturbation strengths of spiral modes which could be responsible for this structure.

[6.03] Efficient Orbit Integration by Scaling for Kepler Energy Consistency

T. Fukushima (*NAOJ*)

Extending the idea of manifold correction (Nacozy 1971) by using the concept of integral invariant relation (Szebehely and Bettis 1970), we propose a new approach to integrate the quasi-Keplerian orbits numerically. The method integrates the time evolution of the Kepler energy and the usual equation of motion simultaneously. Then it adjusts directly the integrated position and velocity by a space scale transformation in order to satisfy the Kepler energy relation rigorously at every integration step. The scale factor is determined by solving an associated cubic equation precisely with help of the Newton method. In treating multiple bodies, the Kepler energies are integrated for each body and the scale factors are adjusted separately. The implementation of the new method is simple, the additional cost of computation is little, and its applicability is wide. Numerical experiments showed that the scaling reduces the integration error drastically. In case of pure Keplerian orbits, the truncation error grows linearly with respect to time and the round-off error does slower than that. When the perturbations exist, a component growing in a quadratic or higher power of time appears in the truncation error but its magnitude is reduced significantly when compared with the case without scaling. The manner of decrease is roughly 5/4 to 5/2 power of the strength of the perturbing acceleration where the power index depends on the type of perturbation. The method seems to suppress the accumulation of round-off errors in the perturbed cases although the details remain to be investigated. In conclusion, the new approach provides a fast and high precision device to simulate the orbital motions of major and minor planets, natural and artificial satellites, comets, and space vehicles at negligible increase of computational cost.

[6.04] A Method of Non-linear Harmonic Analysis and its Application to Determination of Planetary Precession in DE405

T. Fukushima (*NAOJ*) and W. Harada (*Tokyo Univ.*)

We developed a method of non-linear harmonic analysis. The algorithm determines (1) the coefficients of a quadratic polynomial representing the secular variation, the amplitudes and phases of Fourier terms, and the other linear parameters by the usual linear least square method, (2) the frequencies of Fourier terms and the other non-linear parameters by the BFGS algorithm of the quasi-Newton method (Broyden 1967), and (3) the number of the non-linear parameters by increasing it one by one from zero until the residual root mean square (RMS) becomes smaller than the required level for the noiseless data or until its decreasing manner becomes approximately flat for the noisy data. We accelerated the convergence of the algorithm by expanding the set of base functions so as to include the so-called mixed secular terms, namely the product of Fourier terms and a linear function. In order to find suitable initial guesses for the search in the quasi-Newton method, we extended the concept of periodogram to the case of mixed secular terms. As an application of the developed algorithm, we analysed the motion of the unit vector of the heliocentric orbital angular momentum of the Earth-Moon barycenter in the latest lunar/planetary ephemeris, DE405, as Standish (1982) did for DE102. After dropping 86 Fourier terms and 4 mixed secular terms detected, we determined the secular variation of two angles specifying the unit vector in the form of quadratic polynomials as $\gamma = (-0.05240 \pm 0.00014) + (10.55318 \pm 0.00011)t + (0.49318 \pm 0.00004)t^2$, $\varphi = (84381.41127 \pm 0.00006) + (-46.81265 \pm 0.00004)t + (0.04843 \pm 0.00002)t^2$ where the unit is arc second and t is the time since J2000.0 measured in Julian century. This is the latest determination of planetary precession formula in the inertial sense and referred to the ICRF.

[6.05] The Gravity Field of the Saturnian System

R. A. Jacobson (*JPL*)

We have used Saturnian satellite astrometric observations together with the data acquired during the spacecraft flybys of Saturn (Pioneer 11, Voyager 1, and Voyager 2) to develop new satellite and spacecraft ephemerides and a revised gravity field for the Saturnian system. The astrometric data are from the time period 1966 to 2003. The spacecraft data are more extensive than those Campbell and Anderson (1989 *AJ* **97**, 1485) used in their determination of the gravity field. We also included a priori information on Saturn's zonal harmonics from the ringlet constraint devised by Nicholson and Porco (1988 *JGR* **93**, 10209). The gravity parameters found in our analysis are:

Parameter†	Value			Parameter†	Value		
$GM_{\rm system}$	37940683.	±	58.	$\rm GM_{Phoebe}$	0.48	±	0.23‡
$GM_{\rm Mimas}$	2.56	±	0.05	$J_2 \times 10^6$	16294.	±	6.
$GM_{\rm Enceladus}$	5.76	±	1.30	$J_4 \times 10^6$	-921.	±	27.
$GM_{\rm Tethys}$	41.21	±	0.05	$J_6 \times 10^6$	99.	±	28.
$GM_{\rm Dione}$	73.13	±	0.02	$J_8 \times 10^6$	-10.‡		
$GM_{\rm Rhea}$	154.53	±	3.78	$\alpha_{\rm p}$	40.59550	±	0.00360‡
$GM_{\rm Titan}$	8978.09	±	0.88	$\delta_{\rm p}$	83.53812	±	0.00018‡
$GM_{\rm Hyperion}$	0.72	±	0.35‡	$\dot{\alpha}_{\rm p}$	-0.04229‡		
$GM_{\rm Iapetus}$	131.73	±	15.08	$\dot{\delta}_{\rm p}$	-0.00444‡		

† units: GM(km^{3}sec^{-2}), $\alpha_{\rm p}$, $\delta_{\rm p}$ (deg), $\dot{\alpha}_{\rm p}$, $\dot{\delta}_{\rm p}$ (deg century^{-1})

‡ not estimated

The GMs of Hyperion and Phoebe are based on assumed densities of 1.1 ± 0.5 and 1.3 ± 0.5 gm/cm^3, respectively. The Saturn pole right ascension $\alpha_{\rm p}$ and declination $\delta_{\rm p}$ are from French *et al.* (1993 it Icarus, **103**, 163) and their rates are computed from the precession rate of Nicholson it et al. (1999 *BAAS* **31**, 1140).

[6.06] Migration of Asteroidal Dust Particles

S. I. Ipatov (*NRC/NAS, NASA/GSFC, & Inst. Appl. Math., Russia*), J. C. Mather (*NASA/GSFC, USA*), and P. A. Taylor (*University of Maryland, USA*)

We numerically investigated the migration of dust particles with initial velocities and positions same as those of the numbered asteroids using the Bulirsh-Stoer method of integration and took into account the gravitational influence of 8 planets, radiation pressure, Poynting-Robertson drag and solar wind drag, for values of the ratio between the radiation pressure force and the gravitational force β equal to 0.01, 0.05, 0.1, 0.25, and 0.4. For silicate particles such values of β correspond to diameters of 40, 9, 4, 1.6, and 1 microns, respectively. For each $\beta \geq 0.05$ we considered N=500 particles (N=250 for β=0.01). In our runs, planets were considered as material points, but, based on orbital elements obtained with a step of ≤20 yr, we calculated the mean probability of a collision of a particle with a terrestrial planet during the lifetime of the particle. For smaller particles, the ratio of the number of particles that collided with the Sun to the total number of simulated particles and the probability of collisions of particles with the terrestrial planets are smaller. The probability of a collision of a migrating dust particle with the Earth for β=0.01 is greater by a factor of 220 than for β=0.4. The mean time t_a during which an asteroidal dust particle had a semi-major axis 'a' in intervals with a fixed width is greater for smaller β (for the same initial number of particles) at $a < 3$ AU. For $\beta \leq 0.1$ the values of t_a are much smaller at $a > 3.5$ AU than at 'a' between 1 and 3 AU, and are usually maximum at 'a' about 2.3 AU. For β=0.01 the local maxima of t_a corresponding to the 5:6, 6:7, 3:4, and 2:3 resonances with the Earth are greater than the maximum at 2.4 AU. The peaks in distribution of migrating asteroidal dust particles with semi-major axis corresponding to the n/(n+1) resonances with Earth and Venus and the gaps associated with the 1:1 resonances with these planets are more pronounced for larger particles. The spatial density of a simulated dust cloud and its luminosity (as seen from outside) were greater for

smaller distance from the Sun. For example, depending on β they were greater at 1 AU than at 3 AU by a factor of 2.5-8 and 7-25 (4 and 12-13 at $\beta \leq 0.05$), respectively. For the runs without planets, migration outside 5 AU was smaller. More details can be found in http://arXiv.org/format/astro-ph/0303398. This work was supported by NRC (0158730), NASA (NAG5-10776), INTAS (00-240), and RFBR (01-02-17540).

[6.07] HST Astrometry of Saturn's Small Satellites

R. G. French and C. A. McGhee (*Wellesley C.*)

As part of a long-term program to study Saturn's rings over the full range of inclination and phase angles accessible from Earth, we have accumulated over 300 high resolution images of Saturn and its rings with the Hubble Space Telescope's WFPC2 from 1996-2002. Using these images, we have obtained highly accurate measurements of the positions of Saturn's small moons, primarily with the PC chip of the WFPC2. A major result of these investigations is that Pandora and Prometheus are wandering chaotically from their Voyager-based ephemerides, in roughly equal and opposite directions. They seem clearly to be exchanging orbital angular momentum and energy. These results were published in French et al. 2003 Icarus 162, 143-170. In that paper, we compared the astrometric measurements to orbital predictions by R. Jacobson (personal communication), and showed that the typical astrometric accuracy of our measurements is about 0.02 arcsec. There was not room in that paper for the full set of measurements for all satellites, which we present here, and which will be submitted to the NASA Planetary Data System Rings Node. These will be useful for construction of accurate orbital models for all of the observed satellites, and for planning for the upcoming Cassini mission to Saturn.

This work was supported in part by the NASA Geology and Geophysics Program, Massachusetts Space Grant, the Keck Northeast Astronomy Consortium, and the Space Telescope Science Institute.

[6.08] Three-Dimensional Simulations of High and Low-Mass Planets Embedded in Protoplanetary Disks

S. H. Lubow (*STScI*), M. R. Bate (*Univ of Exeter*), G. I. Ogilvie (*IoA*), and K. A. Miller (*Univ of Maryland*)

We analyze the non-linear, three-dimensional response of a gaseous, viscous protoplanetary disk to the presence of a planet of mass ranging from one Earth mass to one Jupiter mass by using the ZEUS hydrodynamics code. We determine the gas flow pattern, and the accretion and migration rates of the planet. The planet is assumed to be in a fixed circular orbit about the central star. It is also assumed to be able to accrete gas without expansion on the scale of its Roche radius. For typical parameters, only planets with masses greater than one-tenth Jupiter's mass produce significant perturbations in the disk's surface density. The flow within the Roche lobe of the planet is fully three-dimensional. Gas streams generally enter the Roche lobe close to the disk midplane, but produce much weaker shocks than the streams in two-dimensional models. The streams supply material to a circumplanetary disk that rotates in the same sense as the planet's orbit. Much of the mass supply to the circumplanetary disk comes from non-coplanar flow. The accretion rate peaks with a planet mass of approximately one-tenth Jupiter's mass and is highly efficient, occurring at the local viscous rate. The migration timescales for planets of mass less than one-tenth Jupiter's mass, based on torques from disk material outside the planets' Roche lobes, are in excellent agreement with the linear theory of Type I (non-gap) migration for three-dimensional disks. We find that it is difficult for planets to acquire as much as ten Jupiter masses before tidal forces cut off further accretion. We acknowledge support from NASA grant NAG5-10732.

[6.09] Lunar and Artificial Satellite Laser Ranging: The Use of Queue Scheduling and Worth Functions to Maximize Scientific Results

P. J. Shelus, R. L. Ricklefs (*University of Texas Center for Space Research*), J. R. Wiant, J. G. Ries (*University of Texas McDonald Observatory*)

The lunar and artificial satellite laser ranging network, part of the International Laser Ranging Service, monitors a large number of targets. Many scientific disciplines are investigated using these data. These include the realization and maintenance of the International Terrestrial Reference Frame; the 3-dimensional deformation of the solid Earth; Earth orientation; variations in the topography and volume of the liquid Earth, including ocean circulation, mean sea level, ice sheet thickness, and wave heights; tidally generated variations in atmospheric mass distribution; calibration of microwave tracking techniques; picosecond global time transfer; determination of the dynamic equinox, the obliquity of the ecliptic, the precession constant and theories of nutation; gravitational and general relativistic studies, including Einstein's Equivalence Principle, the Robertson-Walker b parameter and time rate of change of the gravitational constant; lunar physics, including the dissipation of rotational energy, shape of the core-mantle boundary (Love Number k2), and free librations and their stimulating mechanisms; Solar System ties to the International Celestial Reference Frame.

With shrinking resources, we must not only assess specific data requirements for each target, but also maximize the efficiency of the observing network. Several factors must be considered. First, not only does a result depend critically upon the quality and quantity of the data, it also depends upon the data distribution. Second, as technology improves, the cost of obtaining data can increase. Both require that scientific endeavor pay close attention to the manner in which the data is gathered. We examine the evolution of the laser network, using data analysis requirements and efficient network scheduling to maximize the scientific return. This requires an understanding of the observing equipment, as well as the scientific principles being studied. Queue scheduling and worth functions become important.

This work is funded by: NSF AST-0204127, NASA NAG5-10195, NAS5-01096, NAG5-11464.

[6.10] Coupled Orbital-Rotational-Tidal Dynamics of Io

S. Musotto (*UCLA & Dept. Astronomy, Padova*), F. Varadi, W. Moore (*UCLA & IGPP*), and G. Schubert (*UCLA*)

We will present the results of numerical simulations of the coupled orbital, rotational and tidal evolution of Io. Previous simulations based only on the coupling of orbital and rotational dynamics have shown the presence of forced and free librations for Io, similarly to the librations that have been observed for the Moon, but with a much shorter period. The effect of tides is to damp out the amplitudes of the free librations, therefore simulations including tides will be carried out to determine the most likely rotational state of Io as the end state of the tidal evolution. We will model tides using the classical approach employing a delayed elastic response and using a dynamical integration of the equations of motion within the body. For the dynamical model, a two-layer Maxwell-viscoelastic model of Io

will be used. The results using the two techniques will be compared with analytical results derived from perturbation theory.

[6.11] Stable 1:2 Resonant Periodic Orbits in Elliptic Three-Body Systems

J. Couetdic (*Ecole Centrale Paris*), N. Haghighipour (*DTM/Carnegie*), F. Varadi, and W. B. Moore (*IGPP/UCLA*)

We present the results of an extensive numerical study of the periodic orbits of planar, elliptic, restricted three-body systems consisting of a star, an inner massive planet and an outer massless body in an external 1:2 mean-motion resonance. The dynamics of the outer body of such systems is studied for different values of the mass-ratio of the inner planet and the central star, and also for different values of the orbital eccentricity of the inner planet. Using the method of differential continuation, the locations of the resonant periodic orbits of such systems are identified and their stability is investigated through an extensive study of their phase-parameter space. We present the results of our study and their applications to the extrasolar planetary system GJ876.

We acknowledge the support for this work through NASA Astrobiology Institute/CIW and NASA Astrobiology Institute/UCLA.

[6.12] Getting Physical: Rotation Rate Determination for PHAs

J. G. Ries, E. S. Barker (*UT at Austin, McDonald Observatory*), P. J. Shelus, and R. L. Ricklefs (*UT at Austin, Center for Space Research*)

The NASA Near Earth Object (NEO) search efforts have now discovered more than 2300 objects, 500 of which are classified as Potentially Hazardous Asteroids (PHAs). The McDonald Observatory NEO team continues to participate in the astrometric work of NEO confirmations and follow-up observations. While finding and maintaining precise orbits of these objects is essential in assessing the hazards they might pose to Earth, the physical characteristics such as mass, rotation rate and surface properties are important factors in understanding their full dynamical evolution. The efficiency of the proposed process for transporting objects from the Main Asteroid Belt to Earth crossing orbits (i.e., resonances assisted by the YORP effect) depends on the above properties. At the present we lack sufficient information on the physical characteristics of most NEOs.

As a first step, we are attempting to obtain refined absolute magnitudes, rotational periods, and, whenever possible, axis ratios and three-color information for PHAs. Relative photometry has been already carried out for 2002 EZ11 in the Johnson R band, and more are scheduled. The results of these studies will be presented at the meeting.

This research is funded by NASA's NEO Observation Program grants NAG5-6863 and NAG5-10183.

[6.13] Candidate Asteroids for Discerning General Relativity and Solar Oblateness

J. L. Margot (*California Institute of Technology*)

Shapiro et al. (1968, 1971, 1972) determined the perihelion precession of Mercury and of asteroid 1566 Icarus to test general relativity and to constrain values in the parametrized post-Newtonian formalism. The perihelion shift of Mercury is now known to about 0.1% (Shapiro 1990, Anderson et al., 1992).

Shapiro (1986) emphasized the need to measure the precession of several bodies in order to separate, based on their heliocentric distance dependence, the general relativistic effects from those due to the gravitational quadrupole moment of the Sun (J2). The J2 of the Sun is now known to be of order 2e-7, at a level where it cannot be detected compared to observational error in the Mercury perihelion shift. The J2 measurements rely on helioseismology, solar rotation data, and oblateness determinations.

The recent near-Earth asteroid discoveries provide better opportunities to detect GR and J2 effects. I computed the predicted perihelion advance for the best candidate asteroids, i.e. those with orbital parameters that minimize $a(1-e^2)$ and therefore maximize the sensitivity to J2. About a dozen have long astrometric arcs and perihelion shifts larger than 10"/cy, with the current leading contenders being 2000 BD19 (27"/cy) and 1999 KW4 (22"/cy). These two asteroids and two others (1999 FK21 and 3200 Phaethon) have at least two Earth approaches in the next 4 years during which they will be detectable with the Arecibo radar. The four candidates also have at least five opportunities for radar astrometry before 2020.

With the current best candidate the perihelion precession goes as (1+6e3*J2), assuming that general relativity is correct. A precision of 0.1% or better would be needed to detect the influence of J2. Because obtaining range estimates to the center of mass of asteroids is simpler than contending with the unknown topography of Mercury, this goal may be achievable and may provide the first dynamical measurement of the J2 of the Sun, in addition to probing other potential orbital perturbations.

[6.14] On an Analytical Solution for the Minimum Distance between Two Confocal Elliptical Orbits Used as a Close Approach Filter

M. A. Murison (*U.S. Naval Observatory*) and A. Munteanu (*Benjamin Banneker Academic High School*)

We present an analytical solution to the problem of the minimum distance between two elliptical orbits with common focus. By use of the eccentric anomaly as the independent variable, the algebraic complexity of the solution is reduced. An additional benefit is that one can immediately use the Kepler equation in combination with a very fast and simple integer search algorithm to quickly determine the times of close approach between objects. Thus, one use of the analytical solution is as a fast filter for selecting (for closer scrutiny later) asteroids that will suffer a close approach to a given planet or other asteroid within a specified time, without resorting to numerical integrations.

[6.15] A Search for Asteroids on Earth Horseshoe Orbits

J. L. Margot (*California Institute of Technology*) and P. D. Nicholson (*Cornell University*)

There are currently about a dozen known near-Earth objects with well-determined orbits and semi-major axis between 0.99 and 1.01 AU (Ted Bowell's asteroid database, 2003). We examined their orbital trajectories using the Horizons integrator (Giorgini, 1996) in an effort to find asteroids on Earth horseshoe orbits. Two objects (2002 AA29 and 2000 PH5) displayed a recent abrupt reversal in the evolution of their ecliptic longitude with respect to that of Earth, indicating a classic horseshoe or tadpole behavior. In a Sun-centered frame co-rotating with Earth, their trajectory displays the horseshoe pattern with the expected libration period of 100 years.

2002 AA29 was previously recognized as being on a horseshoe trajectory (Connors et al., 2002). Wiegert et al. (2002) suggested that 2000 PH5 and 2001 GO2 are on horseshoe orbits, although their claim rests on a single 4.5-day observational arc for 2001 GO2.

Although the mean longitude of 2000 PH5 always remains at least 25 degrees away from the longitude of Earth, the asteroid makes very close Earth approaches, within a few lunar distances. This is due to its significant 0.2 eccentricity and the corresponding epicycle-like motion that is superimposed on the libration in mean longitude. The fact that this object happens to have just the right eccentricity to bring it so close to Earth suggests that it may have been barely ejected from the Earth-Moon system into an heliocentric orbit.

Goldstone radar observations conducted by JLM and collaborators show that the object does not appear to be man-made. Higher resolution observations with the Arecibo radar will be conducted in an attempt to constrain its plausible source region. Because of its peculiar origin, repeating close approaches to Earth, and low delta-V, this object may be an attractive target for a sample return mission. A long-lived transponder on its surface would also provide interesting dynamical information.

[6.16] The Distribution in Eccentricity and Inclination, as a Function of the Semi-major Axis of Asteroids

H. Varvoglis and S. Koukioglou (*U. Thessaloniki, Greece*)

We use a running window on the AsDys catalogue of asteroids and create groups of varying proper semi-major axis values. We calculate, for each such group, the distribution of asteroids with respect to proper eccentricity and inclination. We plot the distribution parameters as a function of the semi-major. We see that the graphs are related to the resonant structure in the region of the main Kirkwood gaps.

[6.17] Cutoff Energy Behavior for an Ideal Gas

M. Cahill (*University of Wisconsin, Washington County*)

The energy distribution for an ideal gas is important to dynamical astronomy because it is used as the statistical basis for modeling relaxed dynamical systems. This presentation deals with some fundamental aspects of this distribution.

The microcanonical distribution for a monatomic ideal gas gives the probability that a particle's energy is in a specified range simply as

$$d\psi = c_1 \left(1 - x\right)^{(3N-5)/2} \sqrt{x} dx, \quad c_1 = \frac{2}{\sqrt{\pi}} \frac{\Gamma(3N/2)}{\Gamma(3\left[N-1\right]/2)}, \quad x = \varepsilon / E,$$

where N and E are the total population and total energy of the gas while ε and x are the kinetic energy of the particle in usual and dimensionless forms. The cutoff energy for this distribution occurs when $\varepsilon = E$.

An alternative distribution for this gas may be obtained through most probable methods but it is more complex and given by

$$d\psi = c_2 \rho \sqrt{y}\, dy, \quad c_2 = \left(\int_0^{y_c} \rho \sqrt{y}\, dy \right)^{-1}, \quad y = y_{avg} N \varepsilon / E$$

where y_c is the cutoff value of the dimensionless energy y and ρ is the velocity space density of the phase points of the gas, which can be shown to be given by

$$D\left(\rho\right) = \ln\left(N!\right)/N - y, \quad D\left(z\right) = d \ln\left(z!\right)/dz, \quad y_c = \ln\left(N!\right)/N + \gamma,$$

where γ is Euler's constant.

For the large N case, the energy cutoffs for the microcanonical distribution, ε_{1c}, and that for the most probable distribution, ε_{2c}, are very different and approximately obey

$$\varepsilon_{2c} \sim E \ln N/N = \varepsilon_{1c} \ln N/N.$$

This apparent difficulty is resolved by numerical studies showing that the number of particles in the mirocanonical distribution with energies above ε_{2c} is negligibly small in comparison to N.

[7.01] The GRACE Mission: Status and Early Results

B. D. Tapley (*The University of Texas at Austin, Center of Space Research*), C. Reigber (*GeoForschunzgsZentrumn, Potsdam*), and J. C. Ries (*The University of Texas at Austin, Center of Space Research*)

The Gravity Recovery and Climate Experiment (GRACE) is a dedicated satellite mission whose objective is to map the global gravity field with unprecedented accuracy over a spectral range from 500 km to 40,000 km. The measurement precision will support gravity field solutions in this frequency range that are between 10 and 1000 times better than our current knowledge. The mission profile calls for a gravity field solution with this accuracy every thirty days, which will allow studies of the gravitational signals associated with the mass exchange between the Earths solid, ocean and atmospheric system components. The primary measurement provided by the High Accuracy Inter-satellite Ranging System (HAIRS) is the range change between two satellites orbiting one behind the other at an approximate distance of 200 km. The range change will be measured with a precision better than 10 microns over a ten second averaging interval. A highly accurate three-axis accelerometer, located at the satellite mass center, will be used to measure the surface force and attitude control induced accelerations. Satellite GPS receivers will position the satellites over the earth with centimeter level accuracy. With this set of measurements, GRACE will provide highly accurate measurements of the global gravity field once every thirty days. The two satellites were launched on March 17, 2002 and were designed to operate for a period of five years. The satellites will fly in coplanar nearly polar orbits, at an altitude between 500 and 300 km, separated by approximately 200 km along track. The mission, which is one of the first NASA Earth System Pathfinder Missions, is implemented through a collaborative arrangement by NASA and DLR. The presentation will summarize the mission structure, the early satellite and instrument performance, the data system and ancillary data requirements and will describe some of the early analysis results.

[7.02] The Yale/San Juan Southern Proper Motion Catalog 3.0

T. M. Girard, D. I. Dinescu, W. F. van Altena (*Yale Univ.*), I. Platais (*Johns Hopkins*), C. E. Lopez (*Univ. de San Juan, Argentina*), and D. G. Monet (*USNO - Flagstaff*)

We present the third installment of the Yale/San Juan Southern Proper Motion Catalog, SPM 3.0. Absolute proper motions, positions, and photographic B,V photometry are given for over 11 million objects, down to a magnitude of V=17.5. The Catalog covers an irregular area of 3700 square degrees, between the declinations of -20 and -45 degrees, and excluding the Galactic plane. All observations were made with the 50-cm double astrograph of Cesco Observatory in El Leoncito, Argentina. The Catalog is based on full-plate scans using the USNO Precision Measuring Machine (PMM) and its image detection and

centering software. Almost all SPM fields for which second-epoch plates are available have been included, excepting those in the Galactic plane. The proper-motion precision, for well-measured stars, is estimated to be 4.0 mas/yr. Unlike previous releases of the SPM Catalog, the proper motions are on the International Celestial Reference System by way of Hipparcos Catalog stars, and have an estimated systematic uncertainty of 0.4 mas/yr.

The recently begun SPM CCD survey program is described, also. These observations will provide second-epoch astrometry, as well as improved photometry, for the remainder of the original Southern Proper Motion survey, and for future versions of the SPM Catalog.

This work has been supported by a series of grants from the National Science Foundation, including the current grant, AST-0098548.

[7.03] A Comparison of Large All-Sky Catalogs to the Sky

D. J. Mink, W. R. Brown, and M. J. Kurtz (*Smithsonian Astrophysical Observatory*)

Recent large catalogs, such as the US Naval Observatory's 526,280,881 star A2.0 and 1,036,366,767 star B1.0 Catalogs, the 998,402,801 star Guide Star Catalog II, and the 155,569,249 star (so far) 2 Micron All Sky Survey Point Source Catalog, have revolutionized our ability to do astrometry with CCD images. The recently published FITS World Coordinate System standard has provided a standard way of parameterizing that astrometry, and the WCSTools and SExtractor software packages allow the automation of the "plate-fitting" process. New instruments for ground-based observing, such as multi-fiber spectrographs, need very accurate positions for objects even fainter than those in these large catalogs. As part of a survey to be conducted with one of these new spectrographs, we have amassed 1728 15 by 30 arcminute CCD images of a portion of the northern sky. After matching 200 to 400 point sources per image to the various catalogs and fitting world coordinate systems to them, we present statistics as to how well each catalog matches our portion of the sky.

[7.04] Schlesinger's Telescope: A Brief History of the Yale 26-inch Refractor

W. F. van Altena and E. D. Hoffleit (*Yale University*)

Frank Schlesinger began planning for the establishment of a southern observatory when he arrived at Yale in 1920. After discussing the possibility of a location in Auckland, New Zealand and gathering site survey observations for a four-month period, he decided to select a site in Johannesburg, South Africa. A large photographically corrected 26-inch objective was ground, polished and completed by James McDowell in 1923, while the telescope was built largely in the Yale shops in New Haven. Schlesinger left New Haven in 1924 with the lens, and the telescope followed shortly thereafter. Installation of the 26-inch refractor was completed in early June and dedicated by the Prince of Wales on June 22, 1924. The principal observational program for the 26-inch refractor was the determination of parallaxes of the bright stars and it was continued until 1952, when the telescope was moved to Mt. Stromlo due to the deteriorating sky conditions in Johannesburg. The parallax program continued at Mt. Stromlo until 1963 when the telescope was donated to the Commonwealth Observatory and the Yale-Columbia project moved to Argentina, Columbia having joined with Yale in 1943. Approximately 70,000 plates were taken with the refractor for the parallax programs and about 2,000 stellar parallaxes determined. The Schlesinger 26-inch refractor was destroyed by a firestorm on January 18, 2003, along with the other telescopes on Mount Stromlo, the workshop, library and many of the residences. This event was a sad ending to a telescope that played a major role in defining our knowledge

of the distances, motions and masses of the brighter stars during the first half of the 20th century.

[7.05] New Precession Formulas

T. Fukushima (*NAOJ*)

We adapted J.G. Williams' expression of the precession and nutation by the 3-1-3-1 rotation (Williams 1994) to an arbitrary inertial frame of reference. The new expression of the precession matrix is $P = R_1(-\epsilon)R_3(-\psi)R_1(\varphi)R_3(\gamma)$ while that of precession-nutation matrix is $NP = R_1(-\epsilon-\Delta\epsilon)R_3(-\psi-\Delta\psi)R_1(\varphi)R_3(\gamma)$. Here γ and φ are the new planetary precession angles, ψ and ϵ are the new luni-solar precession angles, and $\Delta\psi$ and $\Delta\epsilon$ are the usual nutations. The modified formulation avoids a singularity caused by finite pole offsets near the epoch. By adopting the latest planetary precession formula determined from DE405 (Harada 2003) and by using a recent theory of the forced nutation of the non-rigid Earth, SF2001 (Shirai and Fukushima 2001), we analysed the celestial pole offsets observed by VLBI for 1979-2000 and compiled by USNO and determined the best-fit polynomials of the new luni-solar precession angles. Then we translated the results into the classic precessional quantities as $\sin\pi_A \sin\Pi_A, \sin\pi_A \cos\Pi_A, \pi_A, \Pi_A, p_A, \psi_A, \omega_A, \chi_A, \zeta_A, z_A,$ and θ_A. Also we evaluated the effect of the difference in the ecliptic definition between the inertial and rotational senses. The combination of these formulas and the periodic part of SF2001 serves as a good approximation of the precession-nutation matrix in the ICRF. As a by-product, we determined the mean celestial pole offset at J2000.0 as $X_0 = -(17.12 \pm 0.01)$ mas and $Y_0 = -(5.06 \pm 0.02)$ mas. Also we estimated the speed of general precession in longitude at J2000.0 as $p = (5028.7955 \pm 0.0003)''$/Julian century, the mean obliquity at J2000.0 in the rotational sense as $\epsilon_0 = (84381.40955 \pm 0.00001)''$, and the dynamical flattening of the Earth as $H_d = (0.0032737804 \pm 0.0000000003)$. Further, we established a fast way to compute the precession-nutation matrix and provided a best-fit polynomial of s, an angle to specify the mean CEO.

[7.06] A Nonlinear Model for the Relative Motion of Satellites

K. T. Alfriend and H. Yan (*Texas A & M University*)

Swarms of small satellites flying in formation is a concept currently being pursued by NASA and the USAF. Most of the studies for identifying potential relative motion orbits for these formations have assumed that the equations of motion in the rotating reference frame centered at the chief or reference satellite can be linearized. The basis for the linearization is the ratio of the satellite separation distance to the orbit radius. There are some formations being for which the separations are too large for the linearization to be valid. In this paper we present a new approach for large formations and introduce a modeling error index for comparing various relative motion theories.

[7.07] The Mass Ratio of Charon to Pluto from Hubble Space Telescope Astrometry with the Fine Guidance Sensors

C. B. Olkin, L. H. Wasserman, and O. G. Franz (*Lowell Observatory*)

The mass ratio of Charon to Pluto is a basic parameter describing the binary system and is necessary for determining the individual masses and densities of these two bodies. Previous measurements of the mass ratio have been made, but the solutions differ significantly (Null *et al.* 1993, Young *et al.* 1994, Null and Owen 1996, Foust *et al.* 1997, Tholen and Buie 1997). We present the first observations of Pluto and Charon with a well-calibrated astrometric instrument – the Fine Guidance Sensors on the Hubble Space Telescope. We observed the motion of Pluto and Charon about the system barycenter over 4.4 days (69% of an orbital period) and determined the mass ratio to be 0.122 $\pm$ 0.008 which implies a density of 1.8 to 2.1 g cm^{-3} for Pluto and 1.6 to 1.8 g cm^{-3} for Charon. The resulting rock-mass fractions for Pluto and Charon are higher than expected for bodies formed in the outer solar nebula, possibly indicating significant post-accretion loss of volatiles.

Based on observations made with the NASA/ESA Hubble Space Telescope, obtained at the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS 5-26555. These observations are associated with proposal #7494.

[8.01] Planet Scattering and Exoplanet Orbits

R. K. Barnes and T. R. Quinn (*Astronomy Dept., U. of Washington*)

We examine the large eccentricities of exoplanets. One possible origin of these orbits results from the ejection of an original companion. We examine systems which lie close to instability, and simulate configurations which eject planets within 10^6 years. We then compare the distributions of eccentricities of the remaining planet, with the observed distribution in single companion systems. We only examine planets whose orbits cannot be partially circularized by stellar tides (typically $P_{orb} \gtrsim 10$ days, $e \lesssim 0.4$). Only 4 planetary systems currently can eject a planet within the observed errors, HD12661, 47UMa, HD82943, and GJ876. For low eccentricities ($e < 0.05$) ejections predict too few planets, for intermediate eccentricities ($0.05 < e < 0.3$), the rate is too high by nearly a factor of 2, but above 0.3, the relative frequencies are in good agreement. At low e planets are most likely not scattered, and their eccentricities result from dynamical friction during the final stage of planet formation. At high eccentricities the results suggest that scattering is the primary mechanism for high eccentricity. The results at intermediate eccentricity however suggest that either there are too few data (both of multiplanet systems and single planet systems) or that another mechanism alters eccentricity, such as collisions, which are not resolved in our simulations. We also find that, for a typical planetary system, semi-major axes do not change by more than 50% after an ejection.

[8.02] Obliquity Variations of Terrestrial Planets in Habitable Zones

K. Atobe, S. Ida (*Tokyo Institute of Technology*), and T. Ito(*National Astronomical Observatory*)

We have investigated obliquity variations of possible terrestrial planets in habitable zones (HZs) in extrasolar planetary systems.

All the extrasolar planets so far discovered are inferred to be Jovian-type gas giants, however, terrestrial planets could also exist in the extrasolar planetary systems. In order for life, in particular for land-based life, to evolve and survive on terrestrial planets, small obliquity variations of the planet is required in addition to its orbital stability, because large obliquity variations may cause significant climate change.

Large obliquity variations are caused by spin-orbit resonances where the precession frequency of a planet's spin nearly coincides with one of the precession frequencies of the planet's orbit. We derived the analytical formulae of obliquity variation amplitude of terrestrial planets in the spin-orbit resonant region. Using the analytical expressions, we evaluated the obliquity variations of terrestrial planets with prograde spins in HZs. Largest obliquity variations are produced by giant planets as far from the HZ as the orbits of the terrestrial planets are hardly perturbed. Stability of the obliquity variations of a terrestrial planet is not associated with its orbital stability.

We found the systems that have terrestrial planets both small obliquity variations and stable orbits in HZs are only 1/5 of the known extrasolar planetary systems. If additional planets are found in the known systems, they generally tend to enhance obliquity variations. On the other hand, a large and/or close satellite that significantly enhances precession rate of the spin axis of the terrestrial planet is likely to reduce obliquity variations of the planet on a stable orbit near 1AU. Moreover, if a terrestrial planet is in retrograde spin state, the spin-orbit resonance does not occur. Retrograde spin, or a large and/or close satellite might be essential for land-based life to survive on a terrestrial planet in a HZ.

[8.03] Dynamical Models of the Planets Orbiting the Star GJ 876 Subject to Doppler and Astrometric Constraints

E. J. Rivera (*Carnegie Institution*) and J. J. Lissauer (*NASA/Ames*)

We present two planet fits to the radial velocity measurements taken at the Keck observatory of the star GJ 876 that account for the mutual perturbations between the planets. Additionally, the guessed parameters that are used to start the iterative procedure to determine the fits are constrained by recent astrometric measurements of the star performed by Benedict et al. (2002; ApJ 581, L115). For some fits, it was also assumed that the planets were nearly coplanar; specifically, the inclinations were within 6° of each other, centered around 25°, and the difference in the nodes was $< 4^\circ$. With fixed inclinations, the $\sqrt{\chi^2_\nu}$ lies in the range 1.62 to 1.66. When the inclinations (and one of the nodes) are fitted, the fitting procedure converged to the same set of parameters for about 80% of the (initial guessed) parameter space surveyed, with a $\sqrt{\chi^2_\nu}$ of 1.6552. In all cases, the mutual inclination was $< 20^\circ$ and the planetary masses were close to their nominal values. Thus, with the astrometric constraints and the assumption that the system is nearly coplanar, these dynamical fits can place strong constraints on the system parameters. Without the astrometric constraints, the fitting algorithm can still find stable systems with large mutual inclinations or with coplanar, but significantly more massive planets.

[9.01] The IAU2000 Standards: The Newly Adopted Time, Coordinates, and Reference Frames

E. M. Standish (*JPL*)

Over the past dozen years or so, the IAU has been deluged with resolutions from Division I (Fundamental Astronomy) regarding dynamics, reference frames, fundamental time-scales, earth orientation, etc. Some of the resolutions are merely cosmetic in nature, detailing the basic foundations which have been used by serious researchers for many years. Some of the other resolutions, however, will have a direct affect upon a number of different fields of study. Sooner or later, these changes will actually be implemented, and they will affect anyone doing precision-type work in astronomy, geophysics, and related fields. As with most changes, there are pros and cons; these will be discussed. On a more practical level, the following questions will be addressed: What major areas of astrometry will be affected? What specific items will change? What does one need to know in order to survive the changes? What does one have to do in order to not be adversely affected?

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

[9.02] The Method of Variation of Constants and Multiple Time Scales in Orbital Mechanics

W. I. Newman (*UCLA*) and M. Efroimsky (*USNO*)

The method of variation of constants is an important tool used to solve systems of ordinary differential equations, and was invented by Euler and Lagrange to solve a problem in orbital mechanics. This methodology assumes that certain "constants" associated with a homogeneous problem will vary in time in response to an external force. It also introduces one or more constraint equations motivated by the nature of the time-dependent driver. We show that these constraints can be generalized, in analogy to gauge theories in physics, and that different constraints can offer conceptual advances and methodological benefits to the solution of the underlying problem. Examples are given from linear ordinary differential equation theory and from orbital mechanics. However, a slow driving force in the presence of multiple time scales contained in the underlying (homogeneous) problem nevertheless requires special care, and this has strong implications to the analytic and numerical solutions of problems ranging from celestial mechanics to molecular dynamics.

[9.03] Gauge-Invariant Disturbing Function in Precessing Frames of Reference

M. Efroimsky (*US Naval Observatory*) and P. Goldreich (*CalTech*)

In most books the Lagrange and Delaunay systems of equations for the orbital elements are derived in the Hamilton-Jacobi approach: one begins with two-body Hamilton equations in spherical or Cartesian coordinates; then carries out a canonical transformation to the orbital elements and, thus, arrives to the Delaunay or Lagrange system. A standard trick then enables one to generalize the approach to the N-body case. We carefully re-examine this step and demonstrate that it contains an implicit condition which restricts the orbit to a certain 9(N-1)-dimensional submanifold of the 12(N-1)-dimensional space spanned by the orbital elements and their time derivatives. This tacit assumption is equivalent to the so-called Lagrange constraint, one that Lagrange imposed "by hand" in order to remove the excessive freedom, when he was deriving his system of equations by the method of variation of parameters.

The physical meaning of this implicit condition, tacitly present also in the Hamilton-Jacobi treatment of the N-body problem, is transparent: it is the condition of the orbital elements being osculating (i.e., of the velocity being expressed through the orbital elements in the same manner as in the two-body case). The imposure of any supplementary condition, which is different from the Lagrange constraint (but is compatible with the equations of motion), is legitimate. However, it will alter the form of the Lagrange and Delaunay equations (Efroimsky 2002, Newman & Efroimsky 2003) and will have consequences for numerical integrators (Efroimsky 2002, Murison & Efroimsky 2003).

Another important alteration of the Lagrange and Delaunay systems will be in order when the disturbing function depends not only upon the coordinates but also upon the velocities, i.e., when the orbital elements are defined in a non-inertial coordinate system (Goldreich 1965).

In the current presentation we consider interplay between these two issues: the freedom of gauge fixing and the freedom of reference-system choice. We apply our results to description of a satellite motion about a precessing planet.

[9.04] Gauge Drift in Numerical Integrations of the Lagrange Planetary Equations

M. A. Murison and M. Efroimsky (*U.S. Naval Observatory*)

Efroimsky (2002) and Newman & Efroimsky (2003) recognized that the Lagrange and Delaunay planetary equations of celestial mechanics may be generalized to allow transformations analogous to the familiar gauge transformations in electrodynamics. As usually presented, the Lagrange equations, which are derived by the method of variation of parameters (invented by Euler and Lagrange for this very purpose), assume the Lagrange constraint, whereby a certain combination of parameter time derivatives is arbitrarily equated to zero. This particular constraint ensures an osculating orbit that is unique. The transformation of the description, as given by the (time-varying) osculating elements, into that given by the Cartesian coordinates and velocities is invertible. Relaxing the constraint enables one to substitute instead an arbitrary gauge function. This breaks the uniqueness and invertibility between the orbit instantaneously described by the orbital elements and the position and velocity components (i.e., many different orbits, precessing at different rates, can at a given instant share the same physical position and physical velocity through space). However, the orbit described by the (varying) orbital elements obeying a different gauge is no longer osculating.

In numerical calculations that integrate the traditional Lagrange and Delaunay equations, even starting off in a certain (say, Lagrange's) gauge, some fraction of the numerical errors will, nevertheless, diffuse into violation of the chosen constraint. This results in an unintended "gauge drift". Geometrically, numerical errors cause the trajectory in phase space to leave the gauge-defined submanifold to which the motion was constrained, so that it is then moving on a different submanifold. The method of Lagrange multipliers can be utilized to return the motion to the original submanifold (e.g., Nacozy 1971, Murison 1989). Alternatively, the accumulated gauge drift may be compensated by a gauge transformation, similarly returning the motion to the original submanifold, or at least to one that is closer to the original. In this paper, we numerically explore the gauge drift using a representative nontrivial example of two planets orbiting the Sun. The Lagrange equations written in a gauge-invariant form are integrated. We present results on (1) rates of the gauge drift and (2) experiments with gauge-motivated correctors.

[9.05] Satellite Orbit Plane Perturbations Using an Efroimsky Gauge Velocity

V. J. Slabinski (*Earth Orientation Dept., U. S. Naval Observatory , Washington, DC 20392*)

Efroimsky(2003) and Newman and Efroimsky(2003) have proposed a generalization of Lagrange's perturbation equations by omitting the requirement that the orbital elements be osculating, that is, that the satellite velocity computed from the unperturbed elements be the same as the velocity computed from the perturbed elements. The arbitrary difference between the two velocities is specified by a "gauge velocity" analogous to the gauge in electromagnetic potentials. This gauge velocity is zero for osculating elements.

As a simple, illustrative example of how this gauge freedom can simplify the resulting element expressions, we compute the J2 gravity perturbations to the plane of a circular satellite orbit. We find the gauge velocity that keeps the orbit inclination constant, with no short-period terms. This gauge velocity then results in a node position that moves uniformly with time, also with no short-period terms.

King-Hele(1958) obtained similar results by a method that implicitly used non-osculating elements. We relate our solution to the first-order osculating element expressions given by

Kozai(1959).

[9.06] Adventures in Coordinate Space

J. E. Chambers (*NASA Ames/SETI Institute*)

A variety of coordinate systems have been used to study the N-body problem for cases involving a dominant central mass. These include the traditional Keplerian orbital elements and the canonical Delaunay variables, which both incorporate conserved quantities of the two-body problem. Recently, Cartesian coordinate systems have returned to favour with the rise of mixed-variable symplectic integrators, since these coordinates prove to be more efficient than using orbital elements.

Three sets of canonical Cartesian coordinates are well known, each with its own advantages and disadvantages. Inertial coordinates (which include barycentric coordinates as a special case) are the simplest and easiest to implement. However, they suffer from the disadvantage that the motion of the central body must be calculated explicitly, leading to relatively large errors in general. Jacobi coordinates overcome this problem by replacing the coordinates and momenta of the central body with those of the system as a whole, so that momentum is conserved exactly. This leads to substantial improvements in accuracy, but has the disadvantage that every object is treated differently, and interactions between each pair of bodies are now expressed in a complicated manner involving the coordinates of many bodies. Canonical heliocentric coordinates (also known as democratic heliocentric coordinates) treat all bodies equally, and conserve the centre of mass motion, but at the cost of introducing momentum cross terms into the kinetic energy. This complicates the development of higher order symplectic integrators and symplectic correctors, as well as the development of methods used to resolve close encounters with the central body.

Here I will re-examine the set of possible canonical Cartesian coordinate systems to determine if it is possible to (a) conserve the centre of mass motion, (b) treat all bodies equally, and (c) eliminate the momentum cross terms. I will demonstrate that this is indeed possible using a new coordinate system, and I will briefly describe the properties and advantages of these coordinates.

[10.01] Kozai Resonantors among Distant Moons of the Jovian Planets

V. Carruba (*Cornell University*), D. Nesvorny (*SWRI*), J. A. Burns, and M. Cuk (*Cornell University*)

S/2000 S5 and S/2000 S6 at Saturn, and S/2001 J10 at Jupiter, three recently discovered satellites that are currently trapped in the Kozai resonance, pose interesting new questions about the origin and dynamics of the jovian planets' moons. Here we report an initial study of this problem where we analyze the current orbits of the moons, as well as the surrounding orbital space. Such a study is central to improve our understanding of the origin of the resonant behavior of S/2000 S5, S/2000 S6, S/2001 J10, and of the distant moons in general.

Above inclination $i = 39.23$ degrees of inclination, two classes of secular evolution are possible: circulation, for which the argument of pericenter goes from 0 to 360 degrees, and libration, for which this angle oscillates around +/- 90 degrees. When we consider the full problem with perturbations from all jovian planets, a chaotic layer emerges near the separatrix between circulating and librating orbits. This chaotic layer must have been crossed by orbits that switched from circulation to libration in the past. Thus, to evaluate the capture efficiency into the Kozai resonance, the size and strength of this chaotic layer must be determined.

Among the methods to determine if an orbit is chaotic or not, the Frequency Analysis Method (Laskar 1993, 1999) is one of the most efficient tools. The main idea of this method is that, for a regular orbit (i.e., the orbit that either lies on a KAM torus or is periodic), the fundamental orbital and secular frequencies are constant with time. By contrast, these frequencies jitter about with time for a chaotic orbit. We determine our system's main frequency (the one that is associated with the precession period of the argument of pericenter) during several consecutive time intervals and check whether sigma(j)= 1-f^j/f^1 (where f^j is the frequency for the j^{th} period) varies with j. This quantity gives a measure of the regular or chaotic behavior of the orbit in question.

We have applied this method to a grid of initial orbits around S/2000 S5. We are currently running simulations with the other satellites. Preliminary results suggest that the chaotic boundary between circulating and librating orbits is asymmetric and fractal. Surprisingly, the orbit of S/2000 S5 is located very close to the chaotic layer. This suggests that S/2000 S5 might have interacted with this layer in the past. Simulations of slow dissipative transition of orbits through this layer are in progress. We believe that these experiments will help us constrain the amount of dissipation that accounts for the capture of these distant moons.

[10.02] Consequences of the Chaotic Motions of Prometheus and Pandora

S. Renner and B. Sicardy (*Observatoire de Paris*)

Recent HST images of Prometheus and Pandora show that their longitudes differ by about 20 degrees from the predictions based on Voyager images. Moreover abrupt changes in mean motion occurred around the end of 2000 (French, R.G. et al., Icarus, in press). These discrepancies are anticorrelated and arise from chaotic interactions between the two moons, the strongest jumps of orbital elements happening at interval of 6.2 years when their apses are anti-aligned (Goldreich, P. and Rappaport, N., Icarus, submitted).

We study the system Prometheus-Pandora using a radau-type integrator taking into account Saturn's oblateness and the perturbations by the major saturnian satellites. We first confirm the chaotic behaviour of the system due to the overlap of four 121:118 apse-type mean motion resonances. Then we show how the available observations suggest values as low as 0.5 g.cm^{-3} for Prometheus and Pandora. These values compare well the densities derived from the density waves excited in Saturn's rings by the two satellites.

Finally we discuss the long-term evolution of the system : using a wide range of initial conditions compatible with observations, we do not detect in general any systematic transfer of angular momentum from Pandora to Mimas via the nearby 3:2 resonances.

[10.03] On the Problem of Phoebe's Family

M. Cuk, J. A. Burns (*Cornell U.*), D. Nesvorny (*SWRI*), B. J. Gladman (*Univ. of British Columbia*), and V. Carruba (*Cornell U.*)

With their large sizes, Himalia and Phoebe are distinguished among the irregular satellites of Jupiter and Saturn, respectively. Their orbital semimajor axes and eccentricities are similar as well; however, Phoebe follows an almost-ecliptical retrograde orbit, quite unlike that of prograde Himalia. Moreover, Himalia has a well-defined dynamical family, whereas Phoebe does not appear to, although several recently discovered irregular satellites of Saturn (2000 S1, S7, S9 and S12) have inclinations like Phoebe's (Gladman *et al.* 2001).

These latter moons have significantly larger orbits than Phoebe's, with several not even crossing Phoebe's path, making a common origin problematic.

To ascertain whether any of the irregulars with orbits close to Phoebe's might be family members, we have run Monte-Carlo simulations that follow the loss and reaccretion of Phoebe-cratering ejecta. None of our runs could produce the presently observed distribution of small retrograde satellites of Saturn. This disagrees with the suggestion of Gladman *et al.* as to the nature of these small Saturnians. If Phoebe had ever been disrupted, these simulations imply that observable fragments should remain on close-by orbits that would not yet have been re-accreted owing to their long synodic periods with Phoebe. What might account for such different histories of similar-sized satellites? Possibly Phoebe was not disrupted whereas proto-Himalia was because orbital velocities are half as much in the former's neighborhood (cf. Nesvorný *et al.* 2003). This is especially relevant since satellite-satellite collisions are much more likely than those with heliocentric impactors (Nesvorný *et al.* 2003). Phoebe's population of craters, to be imaged during Cassini's close flyby on June 12, 2004, may be distinctive because of its collisional history.

[10.04] An Instability in Narrow Planetary Rings

J. W. Weiss and G. A. Stewart (*CU/LASP*)

We will present our work investigating the behavior of narrow planetary rings with low dispersion velocities. Such narrow a ring will be initially unstable to self-gravitational collapse. After the collapse, the ring is collisionally very dense. At this stage, it is subject to a new instability. Waves appear on the inner and outer edges of the ring within half of an orbital period. The ring then breaks apart radially, taking approximately a quarter of an orbital period of do so. As clumps of ring particles expand radially away from the dense ring, Kepler shear causes these clumps to stretch out azimuthally, and eventually collapse into a new set of dense rings. Small-scale repetitions of the original instability in these new rings eventually leads to a stabilized broad ring with higher dispersion velocities than the initial ring. Preliminary results indicate that this instability may be operating on small scales in broad rings in the wake-like features seen by Salo and others.

Some intriguing properties have been observed during this instability. The most significant is a coherence in the epicyclic phases of the particles. Both self-gravity and collisions in the ring operated to create and enforce this coherence. The coherence might also be responsible for the instability to radial expansion. We also observe that guiding centers of the particles do not migrate to the center of the ring during the collapse phase of the ring. In fact, guiding centers move radially away from the core of the ring during this phase, consistent with global conservation of angular momentum.

We will show the results of our simulations to date, including movies of the evolution of various parameters. (Audiences members wanting popcorn are advised to bring their own.)

This work is supported by a NASA Graduate Student Research Program grant and by the Cassini mission.

[10.05] Effect of Slow Variations of Parameters for 2 Co-orbital Satellites and Stationary Configurations for N Co-orbital Satellites

B. Sicardy and S. Renner (*Observatoire de Paris*) V. Dubois (*Universite de Nantes*)

We study the evolution of a test particle co-orbital with a satellite of mass m_s and semi-major axis a_s, orbiting around a planet of mass M_0, under the slow evolution of (1)

M_0, (2) m_s and (3) the variation of the specific angular momentum of the satellite, J_s, caused by a torque.

We show that the particle motion is distorted (with respect to the classical horsheshoe and tadpole orbits) in a manner which is entirely described by dJ_s/dt and by $m_s/(M_0+m_s)$, for any amplitude of the corotation motion.

Adiabatic invariance arguments show that the long term evolution of the particle motion only depends on the variation of $m_s a_s$.

Generalization can be made when a constant torque is applied to the particle as well. If this torque exhibits a radial gradient, however, then the adiabatic invariance of action is destroyed and the evolution of the system must be studied case by case.

We finally investigate the stationary configurations of N co-orbital satellites with unequal masses. We show that if N is even, a relation between the angular separations of the co-orbitals must be verified to permit an equilibrium, with a two-parameter family of possible masses. If N is odd, then for any angular separations of the co-orbitals, there is a one-parameter family of masses which allows equilibrium. The case $N = 3$ can be solved analytically and will be displayed.

[10.06] New Problems and Theories of Synchronous Rotation

F. Varadi (*UCLA*), S. Musotto (*UCLA and Univ. of Padova, Italy*), W. Moore, and G. Schubert (*UCLA*)

The dynamics of synchronous rotation and physical librations are revisited in order to establish a general framework applicable to a variety of problems. The orientation matrix of the body is decomposed around the equilibrium state into perfectly synchronous rotation and deviation. The normal modes of the linearized equations are computed in the case of a circular satellite orbit, yielding both the periods and the eigenspaces of three librations. Libration in longitude decouples from the other two, vertical modes. First, there is a fast vertical mode, with a period very close to the average rotational period. It corresponds to tilting the body around a horizontal axis while retaining nearly principal-axis rotation. In the inertial frame, this mode appears as nutation and free precession. The other, a slow vertical mode, is the free wobble. The effects of orbital inclination are investigated from the point of view of Cassini states. Orbital eccentricity has a surprisingly large effect on physical librations due to an interaction between free precession and wobble. A perturbation theory is outlined to explain the nature of the interaction.

[10.07] Limits on Inclinations in Saturn's Rings

A. S. Bosh (*Boston Univ. & Lowell Obs.*)

In 1995, Saturn occulted the star GSC5249-01240 (Bosh & McDonald 1992); this event occurred when Saturn was in the ring-plane crossing season as viewed from Earth. The data from this event are unusually sensitive to out-of-plane excursions due to the almost edge-on aspect of this event. Previous analyses have shown the F ring to have a significant inclination of 0.0065 deg, or 15 km maximum out-of-plane extent (Bosh et al. 2002). Initial investigation of the remainder of the data set showed that several other features may be inclined as well, e.g. the Titan, Maxwell, and 1.470 Rs ringlets. Results of further analysis of these data will be presented. Support for this work (proposal #HST-AR-08761.01) was provided by NASA through a grant from the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS 5-26555.

[11.01] Formation of Terrestrial Planets in a Dissipating Gas Disk with Jupiter and Saturn

J. Kominami and S. Ida (*Tokyo Institute of Technology*)

We have performed N body simulation on formation of terrestrial planets, including the effect of dynamical friction of gas disk. Jupiter and Saturn are also included in the integrations to see the effect of gas giant planets.

Terrestrial planets are formed through coagulation of protoplanets which are about the size of Mars. Their orbits are almost circular when they are just formed. The eccentricities are gradually pumped up by mutual gravity of the protoplanets and gravitational perturbation due to the giant planets. The orbits start to cross and the protoplanets begin to collide. Eventually, the planets isolate from each other. The eccentricities are still high. During this stage, it is highly possible that partly depleted gas disk is present. This partly depleted gas disk works as gravitational gas drag onto the planets, and lowers the eccentricity. By carrying out N body simulation, Kominami and Ida (2002) showed that Earth-sized planets with low eccentricities can be formed. However, although the final planets' masses and eccentricities are consistent with those of terrestrial planets, the number of final planets tends to be larger than that of our Solar system, which is 4. The average is about 7. During terrestrial formation, it is highly possible that Jupiter and Saturn are already formed. Their existence may trigger further coagulation and can decrease the number of final planets. In this paper, calculations with Jupiter and Saturn are also carried out to see the effect of giant planets on formation of terrestrial planets. We found out that the average number of final planets decrease but not in great amount. The average is about 6.

Meanwhile, the amount of gas changes with time. It depletes as the orbits evolve. We carried out simulations with time dependent amount of gas as well.

By presenting the results, we would like to discuss the effect of gas giant planets onto the formation of terrestrial planets.

[11.02] Constraints on the Size of the Circumplanetary Gas Disk

I. Mosqueira (*NASA Ames/SETI Institute*) and P. R. Estrada (*NASA Ames*)

Based on the dynamical properties of the irregular satellites of Jupiter (Saha and Tremaine 1993; Cuk and Burns 2001) and the separation between the regular and irregular satellites of the giant planets of Jupiter, Saturn, and Uranus, Mosqueira and Estrada (a,b 2003, in press in Icarus) argued that the regular satellites of the giant planets formed in a disk extending out to the position of the irregulars at $\sim R_H/5$, where R_H is the Hill radius of the planet, thus irregular satellites with smaller semi-major axis would have been lost due to gas drag. The recent discovery of irregular satellites of Neptune between $0.17-0.19R_H$ (Nicholson, personal communication) fits with this view (though observational issues cloud the picture to some extent).

But what sets the size of the outer gas disk? One possibility is that the specific angular momentum of gas accreted by Jupiter determines it. Here we explore the alternative possibility that the circumplanetary gas disk once extended farther out, but the resonant tidal torque of the Sun on the circumplanetary gas disk reduced its size. If so, some of the angular momentum of accretion may end up in Jupiter's orbit instead of its spin angular momentum or the angular momentum of the gas-augmented satellite disk. To make progress we need to ask whether any resonant locations of the Sun fall within the disk. Due to the low frequency of the Sun's orbit the $m=2$ horizontal Lindblad resonance falls far from the location of the irregulars at $\sim R_H$. An $m=2$ vertical resonance (Lubow 1981) is located at $\sim R_H/2$, which may set the maximum allowable size for the circumplanetary gas disk, but is still well outside the location of the innermost irregulars. This leads us to consider resonances that arise from the eccentricity of the binary orbit, allowing for the possibility that the eccentricities of the giant planets were significantly larger in the past.

[11.03] Gas Drag Induced Enhancement of the Growth-Rate of Planetesimals

N. Haghighipour (*DTM/CIW*)

It is widely accepted that formation of planets starts with collision and coalescence of small solids in a circumstellar disk. Study of the collisional growth of such solids is of utmost of importance since it furthers our understanding of the early stages of planet formation processes.

Recently Inaba and Wetherill have noted that a gas-giant-forming nebula through the core-accretion mechanism, may be gravitationally unstable. In such an unstable rotating gaseous disk, the pressure of the gas does not change monotonically with distance and it maximizes at certain locations. In a previous study I showed that in such a gravitationally unstable environment, when the motions of solids are restricted to the midplane of the nebula, the combined effect of gas drag and pressure gradients causes solids to rapidly migrate toward the locations of the maximum pressure (Haghighipour and Boss, 2003, ApJ, 583, 996). Such rapid migrations have immediate implications for collisional coagulations of small solids and also for enhancement of the growth-rate of planetesimals.

In this paper I present the results of an extensive numerical study of the orbital evolution and growth of small solids, ranging from micron-sized dust grains to km-sized objects in such a gravitationally unstable disk. Solid objects in this study are free to move in three dimensions and their collisions, coagulations and accretion are taken into consideration. I will show that gas drag induced collisional coagulation can considerably increase the growth-rate of planetesimals, in particular, when the objects grow to sizes of 10 cm to 1 m.

Support for this work through NASA's PGG program and NASA Astrobiology Institute is greatly acknowledged.

[11.04] Viscous Evolution of an Impact Generated Water/Rock Disk Around Uranus.

W. R. Ward and R. M. Canup (*Southwest Research Institute*)

To avoid accretion of substantial hydrogen, it is likely that the final stage of Uranus formation post-dated the bulk of the solar nebula. This renders it unlikely that its satellite system formed from a hydrogen-rich circumplanetary disk, and suggests it might instead be a by-product of a giant impact. Indeed, the 97 degree obliquity of Uranus is often cited as circumstantial evidence that large impacts occurred. Although SPH experiments (Slattery et al. 1989) indicate that sufficient mass and angular momentum can be placed into orbit, it is doubtful that the radius of the resulting disk would be comparable to the dimension of the satellite system; the outer most satellite Oberon resides at 22.3 planetary radii. Here we consider whether a rapid, post-impact spreading of the disk could account for this. The disk is composed primarily of vaporized water and silicates that will condense if the temperature gets too low. A rapid accumulation of the solids would make their further radial transport difficult. On the other hand, the disk temperature can be kept elevated by viscous energy dissipation. We discuss whether a self-consistent model can be constructed and the implied constraints on the effective disk viscosity. Mechanisms such as MHD and/or hydrodynamic turbulence are evaluated as possible sources of the viscosity in this environment.

This research is supported by NASA's Planetary Geology and Geophysics Program.

[11.05] Gas Drag Effects on the Orbital Evolution of Classical Edgeworth-Kuiper Belt Objects After an Early Stellar Encounter.

H. Kobayashi, S. Ida, and H. Tanaka (*Department of Earth and Planetary Sciences, Tokyo Institute of Technology*)

We show that orbital evolution due to aerodynamic gas drag after a stellar encounter can account for the observed bimodal inclination distribution of classical Edgeworth-Kuiper belt objects. We integrate orbits of the objects in classical Edgeworth-Kuiper belt region that acquire high eccentricities and inclinations by a passing stellar encounter, under the influence of gas drag of a protoplanetary disk. Even if their semimajor axes are > 40AU where disk gas density is very low, highly eccentric orbits can be affected by the gas drag because their perihelion distances are small and they pass the dense gas disk regions. The gas drag damps their eccentricities and semimajor axes, but not inclinations. Since the gas drag is more effective for smaller objects, small objects go out from the classical Edgeworth-Kuiper belt region except ones originally having small eccentricities and inclinations. On the other hand, large objects remain with small eccentricities and large inclinations. This result is consistent with the observation.

[11.06] Instabilities of Stellar Disks

M. A. Jalali and C. Hunter (*Department of Mathematics, Florida State University, Tallahassee, FL 32306-4510*)

We investigate the instabilities of the flat isochrone and Kuzmin-Toomre disks using Kalnajs's matrix method. For the unperturbed disks in equilibrium, we introduce a new class of anisotropic distribution functions (DF) in the form $f(E, L_z) = f_0(E) + f_1(E, L_z)$. At first, we prescribe $f_1(E, L_z)$, determine its corresponding surface density and subtract it from the model density. We then reproduce the remainder density by the isotropic part of the DF, $f_0(E)$. The DFs that we generate, enable us to control the population of circular, radial and rosette orbits. We investigate how the populations of these orbits influence the instability of our axisymmetric disks. To compute the matrix elements of Kalnajs's method, we choose orbital frequencies as the integration variables and regularize resonance singularities using the Legendre functions of the second kind. The response of the disk, and its unstable modes are then computed through an iterative scheme.

[11.07] Saturation of the Corotation Resonance in a Gaseous Disk

S. H. Lubow (*STScI*) and G. I. Ogilvie

(*IoA*) We semi-analytically determine the torque exerted in a steady state by an external potential on a three-dimensional gaseous, viscous disk at a non-coorbital corotation resonance. We take into account the nonlinear feedback of the torque on the surface density and vorticity in the corotation region. The ratio of the torque to the value given by the formula of Goldreich and Tremaine depends essentially on a single dimensionless parameter, which quantifies the extent to which the resonance is saturated. The results have implications for the eccentricity evolution of young planets. We acknowledge support from NASA grant NAG5-10732.

[11.08] The Secular Evolution of the Primordial Kuiper Belt

J. M. Hahn (*LPI*)

A model of the secular interactions that are exerted between planets and a particle disk is described. The disk is treated as discrete gravitating rings having a finite thickness h due to the particles dispersion velocities. Since ring-thickness softens their gravitational potentials, the system's time-evolution is readily obtained from the familiar Laplace-Lagrange secular solution for the planets but with the Laplace coefficients softened over a scale h/a.

This rings model is used to simulate a number of Kuiper Belts having masses M=30 earth-masses (eg., its primordial mass) down to its current M=0.1 earth-masses. As long as these Belts are sufficiently thin, these systems are awash in apsidal density and nodal bending waves launched by the giant planets. Initially, long apsidal density waves propagate outwards until they reflect at either the disk's outer edge or at a Q-barrier, whereupon they return as short density waves. These short density waves are nonlinear, i.e., adjacent streamlines are crossed, and this causes the fractional variation in the disk's surface density to exceeds unity.

The giant planets also launch long nodal bending waves which have two possible fates: (i.) bending waves reflect at the disk's outer edge and return as long waves, or (ii.) the waves stall at a site in the disk where the wavelength has become smaller than the disk thickness. This is noteworthy since the accumulation of stalled bending waves can loft particles into high-inclination orbits.

These waves' interesting behavior allow for all sorts of speculative Kuiper Belt histories. For instance, if the edge of this stall-zone migrated inwards to 50 AU due to the Belt's mass-erosion, then wave-stalling can toss distant KBOs into high-inclination orbits as well as terminate the low-inclination component of the Main Belt at 50 AU. Further cosmogonic implications of these waves will also be discussed at conference time.

[12.01] Migration and Dynamical Relaxation in Crowded Systems of Giant Planets

F.C. Adams (*U. Michigan*)

This talk discusses the intermediate-time dynamics of newly formed solar systems with a focus on planetary migration. We consider two limiting corners of parameter space – crowded systems containing $N = 10$ giant planets in the outer solar system and solar systems with $N = 2$ planets that tidally interact with a circumstellar disk. Crowded planetary systems can form via gravitational instabilities and in accumulation scenarios – if the disk is metal rich and has a large mass. The planetary system adjusts itself toward stability by spreading out, ejecting planets, and sending bodies into the star. For a given set of initial conditions, dynamical relaxation leads to a well-defined distribution of possible solar systems. For each class of initial conditions, we perform large numbers of N-body simulations to obtain a statistical description of the possible outcomes. For $N = 10$ planet systems, we consider several different planetary mass distributions; we also perform secondary sets of simulations to explore chaotic behavior and longer term dynamics. For systems with 10 planets initially populating the range 5 AU $< a <$ 30 AU, these scattering processes naturally produce orbits with $a = 1$ AU and the full range of eccentricity. Shorter period orbits (smaller a) are more difficult to achieve. To account for the observed eccentric giant planets, we explore an alternate mechanism that combines dynamical scattering and tidal interactions with a circumstellar disk. This combined model naturally produces the observed range of semi-major axis and eccentricity. We discuss the relative merits of the different migration mechanisms for producing the observed eccentric giant planets.

[12.02] Planetary Growth: From the Gap-opening Mass to the Final Mass of the Giant Planet

P. R. Estrada (*NASA Ames*) and I. Mosqueira (*NASA Ames/ SETI Institute*)

Protoplanets migrate inwards due to the tidal interaction with the nebula disk (Goldreich and Tremaine 1980; Ward 1986). In a minimum mass solar nebula an inwardly migrating protoplanet may open a gap and stall when it reaches a mass between $2 - 15 M_{Earth}$ provided $\alpha < 10^{-4}$ (Rafikov 2002), thus improving its chances of survival. Yet the migration time of a protoplanet in a minimum mass solar nebula may be significantly faster than the formation time of a sufficiently large planetary core ($\sim 10 M_{Earth}$) to allow gas accretion. However, recent analytical work (Tanaka *et al.* 2002) and numerical simulations (D'Angelo *et al.* 2002; Bate *et al.* 2003) have increased the timescale of migration by up to an order of magnitude (depending on disk conditions and whether the corotation resonance saturates or not) compared to previous estimates (Ward 1997). Furthermore, increasing the gas surface density with respect to the minimum mass solar nebula may shorten the formation time of a planetary core (Tanaka and Ida 1999). Provided that a planetary core formed at Jupiter's location in time to open a gap, and that the nebula was weakly turbulent at the time of its formation, gap-opening might have left Jupiter in its present orbit far from the Sun. The issue then arises as to what determines the final mass of the planet. Here we consider the possibility that Jupiter accreted its mass from an annulus of gas within the shocking distance of acoustic waves (Goodman and Rafikov 2001) launched by the growing protoplanet, estimate the gas surface density based on this assumption, and compute the gap-opening critical mass in such a disk. A similar argument applied to the outer giant planets would require lower gas surface densities outside Jupiter, which may be incompatible with a strongly turbulent disk. However, this argument is complicated by the effective viscosity due to the planetary tidal torques themselves. A possible role for the thermal condition will be discussed.

[12.03] Resonant Inclination Excitation of Migrating Giant Planets

E. W. Thommes (*University of California, Berkeley*) and J. J. Lissauer (*NASA Ames Research Center*)

The observed orbits of extrasolar planets suggest that many giant planets migrate a considerable distance towards their parent star as a result of interactions with the protoplanetary disk, and that some of these planets become trapped in eccentricity-exciting mean motion resonances with one another during this migration. Using three-dimensional numerical simulations, we show that resonant migration can also systematically excite large orbital inclinations in pairs of giant planets. Such a mechanism may not be uncommon in the early evolution of a planetary system, and a significant fraction of exoplanetary systems may turn out to be non-coplanar. In fact, non-coplanar embedded planets have already been invoked as an explanation for the warped disk of Beta Pictoris.

[12.04] Pushing Out the 'Cold' Classical Kuiper Belt

H. F. Levison (*SWRI*) and A. Morbidelli (*Nice Obs.*)

One of the most puzzling problems about the Kuiper belt is how it lost its mass. Models of the growth of the large Kuiper belt objects show that there needed to be at least tens of Earth-masses of material in order for the objects we see to grow (e.g. Stern & Colwell 1997 *Astrophy. J.* **490**, 879) and yet much less than a Earth-mass remains (e.g.

Gladman et al. 2001 *Astron. J.*, **122**, 1051). There are significant problems with all of the mass depletion mechanisms thus far proposed. For example, the fact that fragile binary systems exist among the known Kuiper belt objects places so severe a constraint on this process that no mechanism has yet been successful.

Here, we present a new idea in which the *all* the Kuiper belt objects that we see have been pushed outward by the migration of Neptune. In particular, we propose that the original Kuiper belt was massive and had an outer edge someplace between 30 and 40 AU. We present a mechanism by which some of the bodies in this massive disk were temporally captured in the 1:2 mean motion resonance with Neptune. During the outward migration of Neptune these objects were pushed outwards with the resonances only to be released at their current locations. As we will show, this new mechanism produces many of the characteristics of the observed Kuiper belt and is a natural byproduct of migration when the full dynamics is taken into account. This mechanism predicts that the 1:2 mean motion resonance with Neptune will be the outer edge of this population.

[12.05] On the Origin of the Laplace Relation among the Galilean Satellites

S. J. Peale and M. H. Lee (*UCSB*)

The differential migration of the newly formed Galilean satellites induced by disk-satellite interaction leads most of the time to the current configuration of 2:1 resonances among the orbital mean motions n_i, which include the Laplace relation, $n_1 - 3n_2 + 2n_3 = 0$. But if Io and Europa start sufficiently far apart, capture of this pair into resonances at the 5:2, 7:3 or 9:4 mean motion commensurabilities after Ganymede has collected Europa into the 2:1 resonances occurs occasionally. Capture of Io-Europa into a high order resonance depends on Europa's orbital eccentricity being large due to its previously established 2:1 resonances with Ganymede. The Io-Europa high order resonances sometimes become unstable as Europa' eccentricity is further elevated, and migration continues toward the 2:1 commensurability. Callisto is initially left behind in the migration scheme because of its smaller mass and probably a smaller disk surface mass density at its distance from Jupiter, but Callisto might start gaining on Ganymede after the latter's migration is slowed by its coupling with Europa and Io. Callisto is currently near the 7:3 resonance with Ganymede, but there is no obvious means of increasing the orbital eccentricity of either Ganymede or Callisto sufficiently to make capture possible during migration. Io may migrate sufficiently fast to escape capture into the 2:1 resonances with Europa while the disk is in place. Subsequent expansion of Io's orbit due to tides raised on Jupiter can then lead to capture into 2:1 resonances with Europa, and the origin of the Laplace relation would then be due to a combination of processes. Provided higher order resonances can be avoided, capture of the Galilean satellites into 2:1 resonances establishing the Laplace relation is robust for reasonable differential migration rates.

[12.06] Diversity and Origin of 2:1 Orbital Resonances in Extrasolar Planetary Systems

M. H. Lee and S. J. Peale (*UCSB*)

The 2:1 orbital resonances of the two planets about GJ 876 can be easily established by the differential migration of the orbits due to planet-disk interactions. A wide variety of stable 2:1 resonance configurations can be reached by differential migration of planets on initially coplanar and nearly circular orbits. These include configurations with librations of $\theta_1 = \lambda_1 - 2\lambda_2 + \varpi_1$ (where λ_i and ϖ_i are the mean longitudes and the longitudes

of periapse) about 0° and $\theta_2 = \lambda_1 - 2\lambda_2 + \varpi_2$ about 180° (as in the Io-Europa pair), configurations with librations of both θ_1 and θ_2 about 0° (as in the GJ 876 system), and configurations with asymmetric librations of θ_1 and θ_2 tens of degrees from either 0° or 180°. There are however stable resonance configurations with symmetric or asymmetric librations that cannot be reached by capture into resonances by coplanar differential migration. A particular example is the $\theta_1 = 180°$ and $\theta_2 = 0°$ configuration with planets on intersecting orbits. If real systems with these configurations are ever found, their origin would require either a migration scenario involving inclination resonances or multiple-planet scattering in crowded planetary systems.

[12.07] Restricted Three-Body Dynamics and Morphologies of Early Novae Shells and their Spectral Signatures

D. K. Lynch, S. Mazuk, E. Campbell, and C. C. Venturini (*The Aerospace Corporation*)

The goal of this work is to calculate emission line profiles of classical novae systems for comparison to line profiles we observe in an attempt to deduce geometrical and dynamical properties of the system from the spectra. The material ejected by the thermonuclear runaway on the surface of the white dwarf (WD) is modeled as a large number of massless particles that are launched instantaneously and move ballistically thereafter. Each particle's position is propagated independently in three-dimensional space with a particle's track terminating if it impacts the WD or the secondary. Predicted line profiles, assuming an optically thin shell, are generated by computing a histogram of the number of particles in radial velocity space for a given observing projection. At high ejection velocities, a nearly spherical shell is produced. At ejection speeds near the WD's escape velocity, very complicated and ever changing geometries result and the material remains close to the system's barycenter. We present animations of computer simulations of novae shell development and the associated line profiles.

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