American Astronomical Society
Division on Dynamical Astronomy
30th Annual Meeting, April 28 to May 1, 1999
Stanley Hotel, Estes Park, CO

PROGRAM

Tuesday, April 27

4:00p DDA Committee Meeting
6:30p Reception
6:30p Registration (through 8:30p)

Wednesday, April 28

8:20a Registration
8:30a Opening remarks (Hal Levison, Fritz Benedict)

Session 1: Outer Solar System Chaired by *Man Hoi Lee*

8:40a Planetesimal Dynamics and the Formation of Uranus and Neptune,
Martin Duncan **(Invited)**

9:30a Uranus and Neptune: Fugitives from the Jupiter-Saturn Zone?
E.W. Thommes, M.J. Duncan

9:50a The Large Scale Structures in the Outer Solar System: I. Cometary Belts with Resonant Features Associated with the Orbits of Four Giant Planets,
L.M. Ozernoy, N.N. Gorkavyi

10:10a The Large Scale Structures in the Outer Solar System: II. Resonant Dust Belts Associated with the Orbits of Four Giant Planets,
N.N. Gorkavyi, L.M. Ozernoy

10:30a Coffee Break

Session 2: Earth Chaired by *Robin Canup*

10:50a The Dynamical Evolution of the Earth-Moon Progenitors. I. Motivation and Methodology,
J.J. Lissauer, E. Rivera

11:10a The Dynamical Evolution of the Earth-Moon Progenitors. II. Results and Interpretation,
E. Rivera, J.J. Lissauer

11:30a Snowballs from Hell,
A.W. Harris

11:50a Apparent Deceleration of the Lunar Mean Motion and the Uncompensated Time Dilation in Timescales,
S.D. Deines **(Student Stipend)**

12:10p Lunch

Session 3: Solar System Chaired by *Martin Duncan*

1:40p Dynamical Chaos in the Solar System: Past, Current, and Future Research,
Matt Holman **(Invited)**

2:30p Advanced Symplectic Integration of Collisional N-body Systems,
K.P. Rauch, D.P. Hamilton

2:50p Planetesimal Dynamics in a Protoplanetary Disk Perturbed by Massive Companions,
S.J. Kortenkamp, G.W. Wetherill

3:10p The Late Stage of Terrestrial Planet Formation,
C.B. Agnor, R.M. Canup, H.F. Levison

3:30p Coffee Break

Session 4: Rings Chaired by *Mark Showalter*

3:50p Dynamics of Jovian Ring Dust,
J.A. Burns, D.P. Hamilton, M.R. Showalter, P. Thomas, P.D. Nicholson

4:10p Electromagnetic Resonances in Jupiter's Rings,
D.P. Hamilton, K. Rauch, J.A. Burns

4:30p Analysis of Ring Wake Simulations,
M.C. Lewis, G.R. Stewart

Session 5: Poster Presentations 4:50p-6:30p

- ⋆ An Archival Data Survey Around the Hubble Deep Field-South (HDF-S) Region,
K.D. Borne, R.A. White, C.Y. Cheung, E.J. Shaya
- ⋆ Observational Effects of an Inclined F Ring: Eclipses and Occultations,
A.S. Bosh, C.B. Olkin, P.D. Nicholson
- ⋆ Likelihood Centroiding of CCD Point Spread Functions,
W.H. Jeffreys
- ⋆ Dynamical Friction and Planetary Migration,
N. Haghighipour
- ⋆ Global Dynamics of Charged Dust Particles in Planetary Magnetospheres,
J.E. Howard, M. Horanyi, G.R. Stewart
- ⋆ Nearby Stars: A Sample Whose Time Has Come (Again),
P.A. Ianna, T.J. Henry
- ⋆ The Determination and Long Term Integration of the Orbits of Caliban and Sycorax,
R.A. Jacobson
- ⋆ Modeling Asymmetric and Lopsided Galaxy Disks,
S. Levine
- ⋆ Close Pairings of Galilean Satellites Observed Using Speckle Interferometry,
B.D. Mason, G.H. Kaplan, G.G. Douglass, D. Pascu, K. Aksnes
- ⋆ Status of the Second Guide Star Catalog,
J. Morrison, B. McLean
- ⋆ The U.S. Naval Observatory Pole-to-Pole Program,
T.J. Rafferty, E.R. Holdenried
- ⋆ Galaxy Clusters with Rounded Central Density Profiles,
B.F. Smith, R.H. Miller
- ⋆ Orbital Structure of Rotating Triaxial Potentials,
M. Valluri
- ⋆ Planetary Orbits During the Past 100 Million Years,
F. Varadi

Thursday April 29

Session 6: N-body Simulations Chaired by *Hal Levison*

8:20a From NBODY1 to NBODY6: The Growth of an Industry,
Sverre Aarseth **(BROUWER LECTURE)**

9:10a Trajectory Separations Revisited,
R.H. Miller

9:30a Properties of Cores Formed by Retrograde Minor Mergers,
J. Bak **(Student Stipend)**

9:50a Assessing the Limits of N-body Simulations of Clusters of Galaxies,
George Lake **(Invited)**

10:40a Coffee Break

Session 7: A Disk-Planet Interaction and a Killer Asteroid Chaired by *Al Harris*

11:00a Spiral Bending Waves Launched at a Vertical Secular Resonance,
J.M. Hahn, and W.R. Ward

11:20a Asteroid 1997 XF11 Could Collide with Earth,
B.G. Marsden

11:40a Could Asteroid 1997 XF11 Collide with Earth after 2028,
P.W. Chodas, D.K. Yeomans

12:00n Lunch

AFTERNOON FREE

Banquet

6:30p No-host bar

7:00p Dinner

8:15p Time and Tides: An Historical Perspective of the Solar System,
William Ward **(BANQUET SPEAKER)**.

Friday, April 30

Session 8: A Mixture Chaired by *Bruce Smith*

8:20a Binary Star Formation in Magnetic Molecular Clouds,
Alan Boss **(Invited)**

9:10a Supernovae, Magnetic Fields and Magnestars: Dynamical Interaction of a Magnetic Bubble with the Interstellar Medium,
W.I. Newman, A.L. Newman

9:30a On Computer Algebra Generation of Symplectic Integrator Methods,
M.A. Murison, J.E. Chambers

9:50a A New Method for Simulating Gravitational Disk-Planet Interactions,
G.R. Stewart

10:10a Resonant Periodic Orbits in the Three Body Problem,
F. Varadi

10:30a Coffee Break

Session 9: The F Ring and the Shepherds Mystery Chaired by *Joe Burns*

10:50a Saturn's Wayward Shepherds: Pandora and Prometheus,
R.G. French, C.A. McGhee, P.D. Nicholson, L. Dones, J. Lissauer

11:10a Interactions between Prometheus and the F Ring,
M.R. Showalter, L. Dones, J.J. Lissauer

11:30a The Perils of Pandora,
L. Dones, M.R. Showalter, R.G. French, J.J. Lissauer

11:50a The F Ring: Saturn's Crooked Halo,
P.D. Nicholson, R.G. French, A.S. Bosh

12:10p Lunch

Session 10: Astrometry and Proper Motions Chaired by *Phill Ianna*

1:10p Precision Astrometry in Globular Clusters with HST's WFPC2,
Ivan King **(Invited)**

2:00p Parallax and Component Masses of Wolf 1062 (Gl 748) from HST Fine Guidance Interferometry,
G.F. Benedict, B.J. McArthur, O.G. Franz, L.H. Wasserman, T.J. Henry, I. Strateva, P.A. Ianna, D.W. McCarthy

2:30p Astrometry and Orbits of the Inner Satellites of Neptune,
D. Pascu, J.R. Rohde, P.K. Seidelmann, E.N. Wells, J.L. Hershey, B.H.Zellner, A.D. Storrs, D.G. Currie, A.S. Bosh

2:50p The Yale/San Juan Southern Proper Motion Program,
W.F. van Altena, T.M. Girard, I. Platais, V. Kozhurina-Platais, J. Ostheimer, C.E. Lopez, R. Mendez

3:10a The First Year of the UCAC-S Project,
N. Zacharias, S.E. Urban

3:30p Coffee Break

Session 11: Ephemerides Chaired by *Phill Ianna*

3:50p Limitations of the Planetary Ephemerides,
E.M. Standish

4:10p Optimized Chebyshev Polynomial Representations of Ephemerides,
J.L. Hilton, M.A. Murison

Session 12: Business Meeting 4:30p-5:30p Chaired by *Fritz Benedict*

Saturday, May 1

Session 13: Galactic Dynamics Chaired by *Ivan King*

8:20a Transient Spiral Patterns—Support from Hipparcos,
Jerry Sellwood **(Invited)**

9:10a Probing the Structure of the Galaxy with Microlensing,
S.J. Peale

9:30a Resonant Orbits in Triaxial Potentials
D. Merritt

9:50a Evidence for Multiple Mergers among Ultraluminous IR Galaxies,
K.D. Borne, H. Bushouse, L. Colina, R.A. Lucas

10:10a Coffee Break

Session 14: Missions Chaired by *Fritz Benedict*

10:30a FAME—Full-sky Astrometric Mapping Explorer,
P.K. Seidelmann, M.E. Germain, T.P. Green, S.D. Horner, K.J. Johnston, D.G. Monet, M.A. Murison, J.D. Phillips, R.D. Reasenberg, S.E. Urban

10:50a The Precession of a Spinning Spacecraft due to Radiation Pressure Torque,
R.D. Reasenberg

11:10a Searching for Extrasolar Planets with SIM,
S.C. Unwin

11:30a The USNO SIM Grid Star Selection Program,
B.D. Mason, T.E. Corbin, A.R. Hajian, C.A. Hummel, T.J. Rafferty, S.E. Urban, N. Zacharias

Session 15: Late Papers Chaired by *Fritz Benedict*

11:50a Chaotic Tides in Binary Stars and the Three-Body Problem,
R. Mardling

12:10p END

ABSTRACTS

From NBODY1 to NBODY6: The Growth of an Industry (invited paper)

Sverre Aarseth (*Institute of Astronomy, University of Cambridge, UK*) sverre@ast.cam.ac.uk

We review the development of direct N-body codes at Cambridge over nearly 40 years, highlighting the main stepping stones. The first code (NBODY1) was based on the simple concepts of a force polynomial combined with individual time-steps, where numerical problems due to close encounters were avoided by a softened potential. Fortuitously, the elegant Kustaanheimo-Stiefel two-body regularization soon permitted small star clusters to be studied (NBODY3). Subsequent extensions to unperturbed three-body and four-body regularization proved beneficial in dealing with multiple interactions. Investigations of larger systems became possible with the Ahmad-Cohen neighbour scheme which was used over 20 years ago for expanding universe models of 4000 galaxies (NBODY2). Combining the neighbour scheme with the regularization procedures enabled more realistic star clusters to be considered (NBODY5). After a period of simulations with no apparent technical progress, chain regularization replaced the treatment of compact subsystems (NBODY3, NBODY5). More recently, the Hermite integration method provided a major advance and has been implemented on the special-purpose HARP computers (NBODY4) together with an alternative version for workstations (NBODY6). These codes also include a variety of algorithms for stellar evolution based on fast look-up tables. The treatment of primordial binaries contains efficient procedures for chaotic two-body motion as well as tidal circularization, and special attention is paid to hierarchical systems and their stability. This family of N-body codes represents a powerful tool for star cluster simulations which is available to the astronomical community and the massive effort owes much to collaborators.

The Late Stage of Terrestrial Planet Formation

C.B. Agnor, (*U. Colorado, SwRI*) R.M. Canup, & H.F. Levison (*SwRI*) Craig.Agnor@colorado.edu

We performed three-dimenstional N-body integrations of the final stages of terrestrial planet formation. We report the results of ten simulations beginning with 22-55 initial planetary embryos spanning the range 0.5 - 1.5 AU, each with an initial mass of 0.04 - $0.13 M_\oplus$. Collisions were treated as inelastic mergers. We followed the evolution of each system for 2×10^8 years at which time a few terrestrial-type planets remained. On average, our simulations produced 2 planets larger than $0.5 M_\oplus$ in the terrestrial region (1 simulation with one $m \geq 0.5 M_\oplus$ planet, 8 simulations with two $m \geq 0.5 M_\oplus$ planets, and 1 simulation with $m \geq 0.5 M_\oplus$ planets). These Earth-like planets have eccentricities and orbital spacing considerably larger than the terrestrial planets. We also examined the angular momentum contributions of each collision to the final spin angular momentum of a planet, with an emphasis on the type of impact which is believed to have triggered the formation of the Earth's Moon. There were an average of 2 impacts per simulation that contributed more angular momentum to a planet than is currently present in the Earth/Moon system. Our results show that the spin angular momentum states of the final planets are generally the result of contributions made by the last few large impacts. Our results suggest that the current angular momentum of the Earth/Moon system may be the result of more than one large impact rather than a single impact.

Properties of Cores Formed by Retrograde Minor Mergers. (Student Stipend)

J. Bak (*Ohio University*) bak@jeans.phy.ohiou.edu

In the last 10 years over a dozen elliptical galaxies have been observed to posses a core which rotates counter to the rest of the galaxy. In one formation scenario, dynamical friction causes a compact companion to spiral into the center of a much larger elliptical galaxy on a retrograde orbit relative to the larger galaxy's rotation. If the core of the smaller galaxy is not tidally disrupted it may carry some of it's orbital angular momentum to the center. I present results from N-body simulations, which cover the parameter space over which satellite accretion is most likely to form counter rotating cores. The kinematic parts of the results are analyzed using the penalized likelihood method of Merritt to calculate 2D line-of-sight velocity fields, including third and fourth order Gauss-Hermite terms. By combining this method with IRAF, the photometric aspects of the results are analyzed and compared with observations. The results indicate that dissipationless satellite accretion can only form counter rotating cores when the larger galaxy's intrinsic angular momentum is almost perfectly antiparallel to the orbital angular momentum of the satellite. In most other cases a kinematically distinct core is formed. I present statistical properties of the cores, which include the deviations from pure isophote ellipses as well as deviations of the line-of-sight velocity profiles from a pure Gaussian form. To test the robustness of the results, some of the simulations are redone with a minor amount of dissipation added to the satellite. These simulations indicate that including small amounts of gas does not significantly effect the conclusions. I would like to thank the Student Stipend Committee for making this presentation possible.

Parallax and Component Masses of Wolf 1062 (Gl 748) from HST Fine Guidance Sensor Interferometry

G. F. Benedict, B. J. McArthur (*McDonald Obs., U. Texas*), O.G. Franz, L. H. Wasserman (*Lowell Obs.*), T. J. Henry (*Harvard - SAO*), I. Strateva (*Astronomy Dept. U. Texas*), P. A. Ianna (*Astronomy, U. Virginia*), & D. W. McCarthy (*Steward Obs., U. Arizona*) fritz@clyde.as.utexas.edu

We present two independent analyses of astrometric data from FGS 3, a white-light interferometer on HST. Both analyses result in parallax, proper motion and component masses for Wolf 1062 AB (component A, M3.5 V). We relate FGS 3 fringe scanning observations of the science target to a reference frame provided by fringe tracking observations of a surrounding star field. We obtain component masses with a precision better than 5%.

In one approach we determine the relative weighting required to yield parallax and proper motion for a center of gravity for Wolf 1062 AB. This parallax, along with the period and semi-major axis previously derived from the fringe scanning observations by Franz et al. (1998, AJ, 116, 1432), provides a total mass. Individual masses come from the component weighting.

The second approach involves solving simultaneously for reference frame orientation, scale, and the parallax, proper motion, and binary orbital parameters of Wolf 1062 AB.

Finally, we compare radial velocities measured at McDonald Observatory with those predicted from the Franz et al (1998) and our simultaneous solution orbits. The comparison provides an independent check on the parallax.

Evidence for Multiple Mergers among Ultraluminous IR Galaxies

K. D. Borne (*Raytheon Information Technology and Scientific Services*), H. Bushouse (*STScI*), L. Colina (*Instituto de Fisica de Cantabria: SPAIN*), & R. A. Lucas (*STScI*) borne@xfiles.gsfc.nasa.gov

We have used the Hubble Space Telescope to study a large sample of ultraluminous IR galaxies (ULIRGs). We will present a simple morphological classification scheme for ULIRGs. We find that there is very little luminosity variation (in the mean) between the classes, and that there is equal likelihood of a ULIRG being a recent merger (single) as an on-going collision (multiple). It now appears that the fraction of ULIRGs that show evidence for interaction or merging is effectively 100%. Many of the results on ULIRGs are pointing to a complicated dynamical history for this sample of galaxies. One possible explanation for this dynamical diversity is the multiple-merger model proposed by Taniguchi & Shioya (1998, ApJ, 501, L167). We present strong observational evidence for multiple mergers among a large fraction of our ULIRG sample. If this is a valid model, then ULIRGs could be the merger remnants of an earlier generation of compact groups of galaxies.

An Archival Data Survey Around the Hubble Deep Field-South (HDF-S) Region

K. D. Borne (*Raytheon Information Technology and Scientific Services*), R. A. White, C. Y. Cheung (*NASA*), & E. J. Shaya (*Raytheon Information Technology and Scientific Services*)

borne@xfiles.gsfc.nasa.gov

We present the results of a survey of archival data and catalogued objects in the region around the Hubble Deep Field-South (HDF-S). The survey encompasses NASA mission logs, astronomical catalogs, and published journal tables. The HDF-S was the focus of a dedicated HST observing campaign during October 1998. Many astrophysically interesting objects in the vicinity of the HDF-S, including quasars and clusters of galaxies, have been catalogued and observed at a wide range of wavelengths. The byproducts of this and similar user-selected surveys can be used to study classes of objects that may potentially be represented among the faint objects discovered within the HDF-S. For example: information can be obtained about the large-scale structure of galaxy clustering in this region and subsequent predictions can be made with regard to the expected redshift distribution of faint extragalactic sources within the HDF-S. This survey was conducted using a suite of new data search, browse, and visualization tools available at the NASA ADC (Astronomical Data Center: http://adc.gsfc.nasa.gov/).

Observational effects of an inclined F ring: Eclipses and occultations

A. S. Bosh, C. B. Olkin (*Lowell*), & Nicholson P. D. (*Cornell*) amanda@lowell.edu

During the 1995 Saturn ring-plane crossing, Saturn occulted the star GSC5249-01240 (Bosh and Olkin 1996, *BAAS*, **28**, 1124). At this time the ring opening angle was approximately 3 deg, resulting in unusually high sensitivity to inclined features. A fit of the F ring from this and previous events resulted in the first detection of an inclined feature in Saturn's rings (Olkin and Bosh 1996, *BAAS*, **28**, 1125). We find that because the F ring is inclined it in turn blocks and is blocked by the A ring when the rings are in a near edge-on configuration. (Near solar ring-plane crossing, the F ring is instead eclipsed by the main rings.) The degree of obscuration and where it occurs depends on the location of the node of the F ring, which regresses due to Saturn's non-spherical gravity field. This mutual occultation will have an effect on the observed brightness of the rings when near ring-plane crossing and may effect the derived crossing times (Nicholson, French, and Bosh, this conference). Given our current kinematic model for the F ring, we detail the evolution of F ring obscuration near each of the 4 ring-plane crossings in 1995-1996.

Binary Star Formation in Magnetic Molecular Clouds (invited paper)

A. P. Boss (*Carnegie Inst. Wash.*) boss@dtm.ciw.edu

Fragmentation during gravitational collapse has been reasonably successful at explaining the formation of binary and multiple stars. However, nearly all three dimensional collapse calculations have ignored the effects of magnetic fields, whereas magnetic fields are generally regarded as a dominant force in molecular clouds. A few three dimensional collapse models have assumed the presence of a frozen-in magnetic field, but these models did not lead to fragmentation. Recently, three dimensional models that allow for magnetic field loss by ambipolar diffusion have shown that fragmentation is possible for initially prolate, rotating, magnetically-supported cloud cores. The models simulate the effects of magnetic fields by adding the magnetic field pressure term to the gas pressure, an approximation that is valid for clouds with high electrical conductivity and straight magnetic field lines. The magnitude of the magnetic field is assumed to depend on the density raised to a fractional power, as found by previous work on magnetic collapse. Ambipolar diffusion is simulated by reducing the field strength over a time period on the order of 10 cloud free fall times, again in agreement with previous work. The main effect of the magnetic field is to delay the collapse phase. Once collapse begins, a rotating cloud can fragment into a binary protostar, provided that its initial ratio of rotational to gravitational energy (β) exceeds about 0.01. Because the critical value of $\beta \sim 0.01$ falls roughly at the median of the distribution of rotational energies for pre-collapse dense cloud cores, these models provide a plausible explanation for why about half of all primary stars have a binary companion: the initial amount of rotation may be the key quantity.

Dynamics of Jovian Ring Dust

J. A. Burns (*Cornell*), D. P. Hamilton (*U. Maryland*), M. R. Showalter (*NASA-Ames*), P. Thomas, &
P. D. Nicholson (*Cornell*) jab16@cornell.edu

¿From recent Galileo and Keck observations, Jupiter's outermost gossamer rings seem to be collisional ejecta derived from the moons Amalthea and Thebe, whose orbits circumscribe these very faint rings. The rings' visible grains, which are small, evolve inward by Poynting-Robertson drag. The main ring is probably debris from Adrastea, which skims along its periphery. The loss of ejecta from these ring-moons is shown to be heavily influenced by the satellites' size, shape, orbital radius and surface characteristics. Recollision times into satellites are 500-10,000 yrs in the vertically extended gossamer rings but only 20 years for the equatorially confined main ring, accounting for the ring's relative faintness near Metis' path. Mutual particle collisions are rare, allowing the use of single-particle dynamics.

Periodic electromagnetic forces, due to Jupiter's rotating magnetic field, may resonate with the epicyclic frequencies of grains. Such a 3:2 "Lorentz" resonance lies just upstream of where the ring noticeably thickens, while the 2:1 version may drive ring grains into Jupiter's atmosphere. An infinite number of such resonances cluster about synchronous orbit, populating the gossamer ring region. We show through numerical simulations that, for sufficiently slow evolution, resonant trapping should be common. Jumps are not seen in images, implying smaller charge-to-mass ratios than assumed or inadequate image processing.

Could Asteroid 1997 XF11 Collide with Earth After 2028?

P.W. Chodas & D.K. Yeomans (*JPL/Caltech*) paul.chodas@jpl.nasa.gov

Asteroid 1997 XF11 received much notoriety in March 1998 when for a time, orbit solutions indicated that it would make a remarkably close approach to the Earth on October 26, 2028. The miss distance calculated for the orbital solution ssing the observations available on March 11, 1998 (an 8-day data arc), was less than one quarter of a lunar distance, and possibly even smaller, making it easily the closest-ever predicted approach of a minor planet to the Earth. The fairly large size of the asteroid, probably over a kilometer across, also made the object notable. Interest in this object spread rapidly when initial reports to the press suggested that a collision in 2028 could not be ruled out. A complete analysis of the 88-day orbital solution, however, shows that the probability of impact in 2028 was very tiny, essentially zero. A linear analysis of the uncertainties mapped to the target plane in 2028 produces an extremely elongated uncertainty ellipse which does not intersect the Earth. The minimum possible miss distance in 2028 is about 28,000 km. Nonlinear analyses of the uncertainties confirm this result. On March 12, pre-discovery images of the asteroid were found, which greatly strengthened the orbital solution and moved the predicted close approach out to a less remarkable 980,000 km. These observations were not needed to rule out the possibility of a collision in 2028. But using only the 88-day-arc solution, was it possible to rule out collisions after 2028? Linear analyses are inadequate to investigate this question, but nonlinear analyses show that there was indeed a non-neglible probability of impact on the order of 10^{-5} for the year 2040, using the 88-day-arc solution.

Apparent Deceleration of the Lunar Mean Motion and the Uncompensated Time Dilation in Timescales

(Student Stipend)

S. D. Deines (*Iowa State University*) sddeines@inav.net

The histories of the Universal Time (UT) and International Atomic Time (TAI) timescales and the basis for the mathematical models are examined. It appears that a simple special relativistic time dilation correction has been overlooked in the TAI timescale model. This relativistic correction compensates both the apparent deceleration of the lunar mean motion and the 0.8 seconds/year divergence observed between the UT and TAI timescales. The calculated correction of -27.01"/cy2 for the apparent lunar deceleration using special relativity is in close agreement with the observed Lunar Laser Ranging value of -25.9+/-0.5 "/cy2. The calculated timescale divergence is -2.24E-3 seconds per day, which is close to the observed value of -2.16E-3 seconds per day. Evidence is also presented that the timescale divergence can not be due to tidal friction as usually assumed. This raises the issue whether the ultraprecise timescales may need to be evaluated for consistency with Universal Time, the original scientific time standard.

The Perils of Pandora

L. Dones (*Southwest Research Institute, Boulder*), M. R. Showalter (*Stanford University*), R. G. French (*Wellesley College*), & J. J. Lissauer (*NASA Ames Research Center*) luke@boulder.swri.edu

Pandora (1980 S26), the outer "shepherding" satellite of Saturn's F Ring, excites a number of density waves in Saturn's main rings. The back-reaction from the torques excited in wave regions is predicted to cause rapid outward evolution of Pandora's orbit. Pandora shares this timescale problem with Prometheus and other ring moons (P. Goldreich and S. Tremaine, *Ann. Rev. Astron. Astrophys.* **20**, 249 [1982]; J. Lissauer *et al.*, *Icarus* **58**, 159 [1984]). Pandora, however, is unique in that it occupies an orbit that is close to a strong 3:2 resonance with Mimas (e.g., S. P. Synnott *et al.*, *Science* **212**, 191 [1982]; K. Aksnes in *Anneaux des Planétes*, IAU Colloquium 75, Ed. A. Brahic, p. 479 [1984]; N. Borderies et al. in *Planetary Rings*, Eds. R. Greenberg and A. Brahic, p. 713 [1984]). If Pandora *were* in resonance with Mimas, it could transfer angular momentum to Mimas, which Mimas could, in turn, pass on to Tethys by virtue of the 4:2 resonance between Mimas and Tethys. Since Tethys' mass is > 3000 times that of Pandora, the whole system could be held in place. Unfortunately, Pandora does not occupy the 3:2 resonance, at least at the present time.

We will describe the results of orbital integrations of test particles in the Pandora region using the RMVS3 integrator (H. Levison and M. Duncan, *Icarus* **108**, 18 [1994]). Perturbations from Saturn's J_2 and J_4 and Prometheus, Mimas, Tethys, and Titan are included. We will discuss our simulations of the libration in Pandora's orbit due to Mimas recently discovered by C. McGhee et al. (*Icarus*, in preparation [1999]) and by R. French *et al.* (this meeting). The ultimate goal of this research will be to understand the long-term resonant dynamics.

We thank Phil Nicholson and Bob Jacobson for their helpful input to this study.

Planetesimal Dynamics and the Formation of Uranus and Neptune (invited paper)

Martin J. Duncan (*Queen's University*), Harold F. Levison (*SwRI*), Glen R. Stewart (*University of Colorado*), & Edward Thommes (*Queen's University*) duncan@astro.queensu.ca

The question of how Uranus and Neptune formed remains a puzzle, despite the fact that this issue is central to our understanding of the structure of the Kuiper belt (including the scattered disk) and Oort Cloud. In this talk I will review the basic elements of planetesimal dynamics as they relate to this question. I will also present a few preliminary results of our collaboration's N-body simulations using a new symplectic integrator (Duncan, Levison & Lee 1998). The simulations are designed to study the late stages of outer planet formation and illustrate some of the difficulties in forming Uranus and Neptune in this region of the solar system.

Saturn's wayward shepherds: Pandora and Prometheus

R. G. French (*Wellesley C.*), C. A. McGhee, P. D. Nicholson (*Cornell U.*), L. Dones, & J. Lissauer (*NASA/Ames*) rfrench@ahab.wellesley.edu

Saturn's irregular F Ring is flanked by the small satellites Prometheus and Pandora, discovered in Voyager images taken in 1980/81 (Synnott *et al.*, [1983] *Icarus* **53**, 156). Observations with HST during the ring plane crossings in 1995 led to the surprising discovery that Prometheus lagged behind its predicted position by some 19 deg in longitude (Bosh & Rivkin [1996] *Science* **272**, 518; Nicholson *et al.*, [1996] *Ibid* **272**, 509). Subsequent HST observations in 1996, 1997 and most recently October 1998 showed that this lag is steadily increasing by approximately 0.6 deg yr^{-1} (French *et al.*, [1998] *B.A.A.S.* **30**, 1141). This lag remains unexplained. A reexamination of the 1995 HST data now shows that Pandora also deviates from the Voyager ephemeris (McGhee *et al.*, in preparation). Although within one degree of its predicted longitude in 1995, Pandora's mean motion was ~ 4 deg/yr less than expected, corresponding to an increase in the semimajor axis of 1.8 km. Archival HST data from 1994 and additional observations in 1996-1998 reveal a periodic signature in Pandora's mean longitude with an amplitude of about 0.8 deg and a period of ~ 580 days, superimposed on a slow drift of -1.25 deg/yr. While this drift, like that of Prometheus, is unexplained, the oscillatory component matches both in amplitude and phase the expected perturbation due to the nearby 3:2 corotation resonance with Mimas (Dones *et al.*, this meeting). An improved fit is obtained by taking into account the 70 yr. libration in Mimas' longitude due to the 4:2 resonance with Tethys.

The Large Scale Structures in the Outer Solar System: II. Resonant Dust Belts Associated With the Orbits of Four Giant Planets

N.N. Gorkavyi (*NRC/NAS & NASA/GSFC*), L.M. Ozernoy (*George Mason U.*), J.C. Mather (*NASA/GSFC*), & T.A. Taidakova (*Crimean Astrophys. Obs.*) gorkavyi@stars.gsfc.nasa.gov

We present the numerical results on distribution of dust produced by real cometary sources (such as Jupiter-family comets, the Kuiper belt, and Centaur objects) as well as fictitious sources taken from our sample of simulated comets with pericenters between Jupiter and Neptune. The following processes that influence the dust particle dynamics are taken into account: 1) gravitational scattering on four giant planets; 2) planetary resonances; and 3) the Poynting-Robertson (P-R) and solar wind drags. We find that the dust distribution is highly non-uniform, with most of the dust concentrated into four belts associated with the orbits of four giant planets. Typically, a belt has a sharp rise in density on both its edges (depending on the size of particles), especially at the innermost part of the belt. We reveal a rich and sophisticated resonant structure of these belts containing families of resonant particlres and gaps. A dissipative nature of the P-R drag results in specific features of particle capture into, and evolution in, the resonances. The most remarkable part of the simulated circumsolar dust belts is Neptune's non-axisymmetric resonant belt, very dense and flat in the range of 24-67 AU. Its formation is due to the capture of dust particles into the 2:1, 3:2, and other resonances with Neptune. Based on our simulations, we expect a new, quasi-stationary dust population to exist in the belts near Jupiter and Saturn, wich is highly inclined and possesses large eccentricities. This population is basically non-resonant and is an important addition to otherwise resonant dust belts. The simulated dust is likely the main source of the zodiacal light in the outer Solar system, which will be analyzed in our futher work.

Dynamical Friction and Planetary Migration

N. Haghighipour (*University of Missouri-Columbia*) nader@lula.physics.missouri.edu

Numerical integrations of a three-body system consisting of a star and two planets in a uniform interplanetary medium indicate a combination of planetary migration and temporary resonance capture, when the dynamic frictional force of the medium is taken into account. Integrations reveal that the outer planet migrates outwards before being captured in resonance and the duration of this resonance lock is dependent on the value of the density of the medium. After leaving the resonant state, the outer planet continues its outward migration.

Results of a series of numerical integrations for the system of Sun, Jupiter and Saturn with the different values of the density for the interplanetary medium are presented. It is shown that Saturn migrates outwards and becomes captured in a (3:1) resonance with Jupiter. It stays in that state for few hundred thousand years until it leaves the resonance and continues its outward migration. The dynamical behavior of the orbital elements and angular momentum of the two planets, during the migration as well as the resonance, and also the relation between the density of the interplanetary medium and the duration of the resonance lock are discussed.

Spiral Bending Waves Launched at a Vertical Secular Resonance

J. M. Hahn (*LPI*) & W. R. Ward (*SwRI*) hahn@lpi.jsc.nasa.gov

The excitation of spiral bending waves at a vertical secular resonance is investigated. These nodal bending waves are launched at sites where the secondary's nodal regression rate matches the disk's rate, and they propagate in both particle and gas disks. In planet-forming environments where the local disk mass is often in excess of the secondary's mass, the resonance lies quite close to the secondary's orbit a_s, and the bending waves have a wavelength $\sim (ha_s)^{1/2}$ where h is the disk scale height. However disk stirring by the secondary or gap formation tends to weakens the wave interaction by slowing the secondary's nodal regression rate and pushing the resonance radially away. The excitation of nodal bending waves also damps out the secondary's inclination which ultimately shuts off subsequent wave generation. For instance, an Earth-mass protoplanet embedded in a minimum-mass planetesimal disk will have its inclination damped out in $\sim 10^2$ to 10^3 orbits if there is no gap or stirred zone, and a Jovian-mass protoplanet orbiting in a minimum-mass nebula gas disk will lose its inclination in $\sim 10^3$ orbits if it resides in a gap. Additional consequences of the bending-wave phenomenon in planet-forming systems shall also be discussed.

Electromagnetic Resonances in Jupiter's Rings

D.P. Hamilton, K. Rauch (*U. Maryland*), & J.A. Burns (*Cornell U.*) hamilton@astro.umd.edu

Voyager and Galileo images have shown that Jupiter's ring consists of several components: 1) a 10,000 km wide main ring associated with the satellites Metis and Adrastea, 2) a vertically-extended halo located inward of the main ring, and 3) Gossamer rings associated with the small satellites Thebe and Amalthea. The gross properties of the rings are probably due to electromagnetic forces, which cause resonances at specific locations, and Poynting-Robertson drag, which makes orbits evolve inward. First-order electromagnetic, or Lorentz, resonances seem to bound the inner and outer edges of the jovian ring halo, while in the outer gossamer ring, these vertical Lorentz resonances are strong enough to trap dust grains smaller than a few microns in radius and systematically drive them to high inclinations.

Additionally, we have found two new and interesting sets of resonances near synchronous orbit. Both sets are second-order resonances, where the small quantities are orbital eccentricities and inclinations in one case and the strength of the perturbation forces in the other. Both sets of resonances have analogs in gravitational systems. These resonances affect the orbital properties of ring particles near synchronous orbit, and may lead to observable features in the structure of the ring. Indeed, Voyager noted an enhancement in density near synchronous orbit, although Galileo observations do not confirm this observation.

Finally, we have implemented a symplectic integrator capable of handing an array of perturbations affecting dust: planetary, solar, and satellite gravity, radiation pressure, and the velocity-dependent Lorentz force. We are currently running tests to determine circumstances under which the new integrator is superior to more commonly used Runge-Kutta and Bulirish Stoer algorithms and will report our initial findings.

Snowballs from Hell

A. W. Harris (*Jet Propulsion Laboratory, Caltech*) awharris@lithos.jpl.nasa.gov

Frank and Sigwarth [e.g. Rev. Geophys. 31, 1 (1993), J. Geophys. Res. 104, 115 (1999)] have for many years promoted the hypothesis of a population of small "house-sized" comets in near-parabolic orbits nearly tangent with the Earth's, raining down on the Earth at a rate of $\sim$ 20/minute, based on "holes" in the dayglow of the Earth's atmosphere, observed first by the Dynamics Explorer 1 satellite, and more recently by the Polar satellite. One of the key aspects of the claimed observations is that the atmospheric holes appear to be more numerous on the morning hemisphere of the Earth, to which Frank and Sigwarth draw analogy to radar meteors, which show a similar asymmetry. In this paper, I show that the distribution of orbits posited by Frank and Sigwarth yield the opposite asymmetry from the claimed observations. The only class of orbits which yield the correct diurnal asymmetry, and preserve acceptably low entry speeds, are orbits interior to the Earth's, with perihelia near the orbit of Mercury. Icy bodies in such orbits would indeed be "snowballs from hell."

Optimized Chebyshev Polynomial Representations of Ephemeride

J.L. Hilton, & M.A. Murison (*U.S. Naval Observatory*) jhilton@briemann.usno.navy.mil

High-precision planetary ephemerides have accuracies of about one part in $10^{10} - 10^{12}$, and span several centuries. This leads to a storage space problem for these ephemerides. We developed a computer program to optimize conversion of orbital ephemerides from tabular form to Chebyshev polynomials (see Newhall, X X 1989, *Celest. Mech.*, 45, 305-310) for compact storage and speedy interpolation. This program was used to numerically determine the optimal mean anomaly segment length for an orbit. Each segment is fitted with the Chebyshev polynomial of minimum order needed to yield a specified precision. At the level of precision needed for high precision ephemerides, the file size increases by about 10% when the precision of the Chebyshev polynomials is increased by an order of magnitude, regardless of segment length.

File sizes continuously shrink as segment length is increased for low-eccentricity Keplerian orbits (e $<$ 0.5). At higher eccentricities, Keplerian orbit file sizes reach local minima near segment lengths that are simple fractions of a complete orbit. For ephemerides of 15 asteroids, the file size becomes approximately constant for segment lengths greater than about 90 degrees. The file size is independent of the orbital eccentricity and depends linearly on the semi-major axis.

The file sizes for the outer planets, Saturn through Pluto, also become constant, but for segment lengths greater than about 45 degrees. Also, the file sizes increase linearly with semi-major axis, but the slope of the increase is lower. Dynamical studies using fictitious bodies are currently being conducted to understand this behavior.

The file sizes for the Moon and Venus are similar to those of Keplerian orbits of eccentricity 0.1, while the remaining planets produce optimized file sizes intermediate between the lunar and outer planet extremes.

Dynamical Chaos in the Solar System: Past, Current, and Future Research (invited paper)

Matt Holman (*Smithsonian Astrophysical Observatory*) mholman@poincare.harvard.edu

In the last two decades remarkable advances in computer speed, the development of new numerical techniques, and the application of modern nonlinear dynamics techniques to classical problems of celestial mechanics have permitted the discovery and exploration of a number of examples of dynamical chaos in our own solar system. Perhaps the most interesting is the result that the orbits of the planets themselves evolve chaotically. I will review both past and current research on this topic and describe a number of avenues of future research in solar system dynamics.

Global Dynamics of Charged Dust Particles in Planetary Magnetospheres

J. E. Howard (*Center for Integrated Plasma Studies, University of Colorado*), M. Horanyi, &
G. R. Stewart (*LASP, University of Colorado*) jhoward@juno.colorado.edu

We study the global stability of charged dust grains orbiting an axisymmetric planet with co-rotating magnetic field. The magnetic field and induced electric field are described in an inertial frame using the magnetic stream function Ψ. The combined gravitational, magnetic, and electric forces are modelled by a two-dimensional effective potential $U^e(\rho, z)$, parametrized by the conserved angular momentum p_ϕ. The critical points of U^e then locate the equilibrium circular orbits, nonequatorial as well as equatorial. The stable equilibria form the nuclei of potential wells, which can contain large populations of dust grains. These potential wells have their own topological structure, so that a particle which loses local stability can still be trapped *globally*. Explicit Lyapunov stability boundaries ar derived for both positive and negative charges in both prograde and retrograde orbits. Thus, radial stability is lost when a critical point undergoes a tangent bifurcation, while transverse stability is lost via a pitchfork bifurcation. For a given position near a given planet stability depends only on the charge-to-mass-ratio q/m, which for a spherical dust grain is proportional to Φ/a^2, where Φ is the ambient plasma potential and a is the grain radius. The results are applied to Saturn and Jupiter.

Nearby Stars: a sample whose time has come (again)

P. A. Ianna (*UVa*) & T. J. Henry (*CfA*) pai@virginia.edu

In the first quarter of this century a large proportion of astronomical research focused on working out distances and luminosities for stars in our neighborhood. As astrophysics developed the emphasis shifted outwards to the farthest reaches of the Milky Way and the galaxies beyond.

Following a period of relative neglect, there is renewed interest in nearby stars in the wake of the discoveries of extrasolar jovian planets, and circumstellar and planetary debris disks. Future space missions will have unprecedented sensitivity to the detection of planets around nearby stars. In order to have the best possible target list for those missions, it is vital to fill gaps in our knowledge of the nearby stars and to identify as completely as possible those stars within 20 pc or so of the sun. Evidence suggests we may know less than half the stars in this sample!

To remedy the situation NASA has initiated the NStars Project (D. Backman, Project Scientist; T. Henry, Deputy Project Scientst) within the Astrobiology Institute at Ames Research Center. The goal of NStars is to discover and characterize all stars within 20 pc and provide a web-accessible fully relational database (http://nstars.arc.nasa.gov) for all nearby stars.

The Determination and Long Term Integration of the Orbits of Caliban and Sycorax

R. A. Jacobson (*JPL/Caltech*) raj@murphy.jpl.nasa.gov

The first 2 irregular satellites of Uranus, Caliban and Sycorax, were discovered in late 1997 (Gladman *et al*. 1998 *Nature* **392**, 897). Subsequently, pre-discovery observations of both satellites were found on plates taken by D. Cruikshank in June of 1984. Recently, P. Nicholson, D. Tholen, and W. Offutt provided observations which they made in late 1998 at Palomar Mountain, Mauna Kea, and Cloudcroft, respectively. I fit a numerical integration perturbed by the Sun, Jupiter, Saturn, and Neptune to the set of available observations. For the 47 observations of Caliban the respective rms values of the $\Delta\alpha\cos\delta$ and $\Delta\delta$ residuals are $0''.60$ and $0''.32$, and for the 103 observations of Sycorax the analogous values are $0''.57$ and $0''.59$.

I extended the integration to span a 6000 year period and computed osculating orbital elements at yearly intervals. The table below contains the mean values of the elements over the 6000 years, the sidereal period, and the precession periods of the argument of periapsis and longitude of the ascending node. The osculating elements (except for a) exhibit a significant long period oscillation with a period roughly half that of the argument of periapsis.

Element	Caliban	Sycorax
a (km)	7166840	12191450
e	0.168	0.520
ω (deg)	153.32	20.99
i (deg)	140.93	156.99
- (deg)	168.00	263.69
P (day)	579.46	1283.26
P_ω (yr)	8900	1390
P_- (yr)	6700	1860

Ephemerides for the satellites are available electronically from the JPL Horizons on-line solar system data and ephemeris computation service.

Likelihood centroiding of CCD point spread functions

W. H. Jefferys (*University of Texas at Austin*) bill@clyde.as.utexas.edu

Traditionally, least squares has been used for fitting point spread functions (PSFs) to observed CCD data. However, and particularly at low signal levels, the ability of CCDs to count individual photons and the CCD readout noise conspire to produce a likelihood function that may differ significantly from the standard least-squares likelihood. This suggests that modelling the likelihood function directly may result in improved centroiding. In this paper I report on some preliminary investigations relevant to the FAME project on likelihood fitting of PSFs.

Precision Astrometry in Globular Clusters with HST's WFPC2 (invited paper)

I. R. King & J. Anderson (*University of California, Berkeley*) king@glob.berkeley.edu

Using 15 images of the same field in a globular cluster, we achieve a positional accuracy better than 0.01 pixel for each star, so that internal proper motions are measurable over intervals as short as two years. Comparison of the dispersion of thousands of proper motions with that of thousands of radial velocities should, when the latter are available, yield the most accurate distances for globular clusters (good to a few per cent). The proper motions themselves should yield a wealth of new information about the dynamics of the clusters. Our methods are aimed at removing the systematic error connected with the positioning of a star with respect to pixel centers. The crucial step is to obtain a very accurate PSF, which we derive by an iteration between PSF shape and star positions in the individual images. We introduce the concept of the *effective PSF*, which is a continuous function derived by ingegrating the instrumental PSF over a pixel at all possible positionings. We avoid global plate solutions by transforming each star from image to image relative to a tight grid of its immediate neighbors. We have also developed procedures for dealing with the spatial variation of the PSF, and strategies for effective dithering of multiple images.

Planetesimal Dynamics in a Protoplanetary Disk Perturbed by Massive Companions

S. J. Kortenkamp & G. W. Wetherill (*Carnegie Institution of Washington - DTM*) kortenka@dtm.ciw.edu

Most conventional models of planet formation begin with a protoplanetary disk of gas and dust orbiting a central protostar. During the early evolution of this disk it is believed that the dust particles coagulate into larger planetesimals in the 0.1 to 10 kilometer size-range. In a swarm of such planetesimals gas drag and mutual gravitational interactions become important factors in the continued growth of the bodies. The mutual gravitational interactions effectively randomize the orientation of the planetesimal orbits (longitudes of pericenter and node) and nearly all modeling of the growth of planetesimals into planetary embryos relies on this assumption of randomized orientation. However, this fundamental assumption may not be valid in protoplanetary systems which include massive companions such as stars, brown dwarfs or early-formed giant planets. In the model we are currently investigating we assume Jupiter and Saturn formed quickly ($\sim 10^2$ years) via disk instabilities (Boss, *ApJ* **503**, 923, 1998) rather than the conventional core-accretion mechanism ($\sim 10^6$ to 10^7 years). Gas drag and secular perturbations combine to produce size-dependent forced orbital elements for planetesimals of different sizes at the same semi-major axis. Similar sized bodies evolve in phase and have relatively low encounter velocities despite their moderately high forced eccentricities and inclinations. With the passage of time this phase coherence begins to breakdown for two reasons. First, differential secular precession randomizes the orbital phasing over the small range in semi-major axis across which orbital crossing is theoretically possible. Second, if the bodies have grown large enough their random mutual perturbations become comparable to the secular perturbations. The time-scale for these mechanisms depends on the sizes and semi-major axes of the planetesimals and companions. Our current efforts are focused on taking these conditions into account in modeling the growth of planetary embryos near 1 AU and in the asteroid belt.

Assessing the Limits of N-body Simulations of Clusters of Galaxies (invited paper)

George Lake (*University of Washington*) lake@hermes.astro.washington.edu

I will report collisionless N-body simulations of galaxies and clusters that are formed from Cold Dark Matter Initial conditions. Among the results from these simulations are:

1) Clusters of galaxies form with roughly the right distribution of lumps, there is no overmerging problem.
2) Galaxies appear as scaled versions of clusters. They fail to overmerge and form smooth systems. Since an L_* galaxy in a cluster scales to roughly an LMC within a galaxy halo, there are dozens of LMCs and thousands of dwarfs in a simulated galaxy.
3) Reports of universal profiles and ”cores” in simulations owed to poor resolution. Increasing the resolution produces profiles without cores that may well be a poor match to cosmological structure.

The issue of ”cores” within N-body simulations is very interesting. Of course, a core implies a maximum phase density or a lack of information. One way to miss information is to simulate fewer particles. Just how is the maximum phase density achievable in a simulation related to the number of simulated particles? What physical mechanisms might generate the cores that (we think) we see in real systems? I will reject some of the easy answers to these questions and appeal for your collective wisdom to be brought to bear on the problem.

Modeling Asymmetric and Lopsided Galaxy Disks

Stephen Levine (*U.S. Naval Observatory Flagstaff Station*) sel@nofs.navy.mil

Lopsidedness is common in both dwarf galaxies and large spiral galaxies. Asymmtries are usually seen in the displacement of the bright inner parts of the disk with respect to the outermost isophotes, and are particularly common in small low-luminosity galaxies. If the galaxy has an extended dark halo with a soft core, and the disk rotation is retrograde relative to the disk's orbit in the halo, then a bulk asymmetry can survive for an extended period. The observational consequences include asymmetries in the distribution of light, and in the velocity fields of the stars and gas.

Analysis of Ring Wake Simulations

M. C. Lewis & G. R. Stewart (*Laboratory for Atmospheric and Space Physics*) ml@colorado.edu

Collisional N-body simulations at the edge of a perturbed planetary ring are used to model the edges of the Encke gap in Saturn's rings. A small satellite, Pan, orbits inside the Encke gap and excites forced eccentricities and density wakes on both edges of the gap. The simulations use a local cell method to model a narrow ring using particles of the appropriate size for the A-ring at the proper optical depth. In the simulations we see evidence for shear reversal at the wake peaks. Our results imply that the most significant factor in the damping of the wakes is the reduction of the forced eccentricity and not randomization of the phase angles of the particles. The reduction of the forced eccentricity occurs in an orderly fashion with steep drops at each successive wake maximum following the highest density wake peak.

At the inner edge (that nearer the perturber) we see phase shifts visible as bending of the line wake maxima. Because the simulations are actually of narrow rings, we also see a number of interesting phenomena at the outer edge. A strong boundary layer forms at that edge, which becomes partially detached from the rest of the ring. The wake patterns persist much further downstream in this boundary layer than they do in the rest of the ring. We also observe that in the less dense region between the main section of the ring and the boundary layer the magnitude of the forced eccentricities reverse their behavior in the main part and increase at each wake maxima.

At the talk we will compare our results to the various analytic theories of Borderies, Goldreich, and Tremaine.

The Dynamical Evolution of the Earth-Moon Progenitors I. Motivation and Methodology

J. J. Lissauer (*NASA Ames Research Center*), E. Rivera (*Dept. of Physics & Astronomy, SUNY Stony Brook*), M. J. Duncan (*Dept. of Physics, Queen's University, Kingston ON*), & H. F. Levison (*SwRI*)

lissauer@ringside.arc.nasa.gov

The Giant Impact Hypothesis was introduced in the mid-1970's after consideration of results from the Apollo Moon missions. This hypothesis best explains the similarity in elemental proportions in lunar and terrestrial rocks, the depletion of lunar volatiles, the lack of lunar iron, and the large angular momentum in the Earth-Moon system.

Comparison between the radiometric ages of inclusions in the most primitive meteorites and those of inclusions in the oldest lunar rocks and the differentiation age of Earth suggests that the Earth-Moon system formed about 100 Myr after the oldest meteorites. In addition, the age of the famous Martian meteorite ALH84001 and an early solidification time estimated from the Martian crust, suggest that the inner Solar System was fairly clear of large bodies about 10 Myr after the oldest meteorites formed. Thus, the "standard model" suggests that for a period of several tens of millions of years the terrestrial planet region had few, if any, lunar-sized bodies and there were five terrestrial planets, Mercury, Venus, the two progenitors of the Earth-Moon system, and Mars.

To simulate the dynamics of the Solar System before the hypothesized Moon-forming impact, we are integrating the Solar System with the Earth-Moon system replaced by two bodies in heliocentric orbits between Venus and Mars. The total (orbital) angular momentum of the Earth-Moon progenitors is that of the present Earth-Moon system, and their total mass is that of the Earth-Moon system. We are looking at ranges in mass ratio and initial values for eccentricity, inclination, and semi-major axis. We are using the SYMBA integrator (Duncan *et al.* 1998, *Astron. J.* **116,** 2067) to integrate these systems until a collision occurs or a time of 200 Myr elapses. Results are presented in a companion paper.

Chaotic Tides in Binary Stars and the Three-Body Problem

Rosemary Mardling (*Monash University, Australia*) ro@spiral.maths.monash.edu.au

It has been known since the days of George Darwin that a binary is unstable to mass transfer if its component stars approach each other within a certain distance. Recently, I showed that a second type of tidal instability exists in close binaries when their orbits are eccentric (Mardling 1995, ApJ, 450,722). This instability involves a chaotic interaction between the orbit and the tides of at least one of the stars with the possibility of huge tides being raised, in contrast to normal tidal interactions where tidal energies are relatively small. In this talk I will show that the binary-tides problem is intimately related to the three-body problem. While the stability against exchange in a hierarchical triple may be examined in a way similar to Roche stability against mass transfer in a close binary, stability against escape of the outer body of a hierarchy, in particular one which is forbidden energetically to exchange with an inner component, has not been well understood. I will propose a correspondence between the binary-tides problem and the three-body problem, and show that stability against escape in a triple is predicted by a formula almost identical to that which predicts chaotic tidal interactions in a close binary. I will outline a framework based on the notion of "modes of oscillation" of a binary and show how this may be used to predict approximately the evolution and final (unbound) configuration of an unstable hierarchical triple with arbitrary masses and initial configuration.

Asteroid 1997 XF$_{11}$ Could Collide with Earth

B. G. Marsden (*Harvard-Smithsonian Center for Astrophysics*) bmarsden@cfa.harvard.edu

Early in 1998, the 2-km asteroid 1997 XF$_{11}$ became of interest as a possible danger to the earth because it would clearly pass within–possibly well within–the earth's sphere of influence on 2028 Oct. 26 (*IAUC* 6837). Given the usual model of the solar system, the 2028 passage was entirely predictable in that there was then no possibility of collision with the earth (*IAUC* 6879). Nevertheless, despite this predictability, several colleagues insisted on estimating impact probabilities, with results ranging from 10^{-3} to 10^{-1117}; although this latter figure by Muinonen may be technically correct, it surely invites the imagination of bizarre scenarios that would increase it. Surprisingly, despite a stated desire for "peer review" of pronouncements of an asteroid hazard, there was no consideration that 1997 XF$_{11}$ might have posed a danger to the earth a few years *after* 2028. Given the 88-day arc of observations, the uncertainty in the 2028 miss distance meant that the object's revolution period, currently 1.73 years, could subsequently have been anything from 1.53 to 1.99 years. Furthermore, the essentially linear annual change of 4000 km in the minimum distance between the earth's orbit and the object's descending node would reduce this distance to zero during the late 2030s. Given the possibility of a post-2028 earth-resonant period such as 5/3, 7/4, 9/5 or 12/7 years, it was also predictable that there existed trajectories for 1997 XF$_{11}$, entirely consistent with the available observations, that would yield an earth impact during this timeframe. A possible deep impact in 2040, a grazing impact in 2037 and other passages within 2 or 3 earth radii were in fact found. Although the chaos induced in 2028 renders the calculation of impact probabilities rather difficult, a simplistic argument gives a value of about 10^{-5} in at least one of the relevant years (albeit at a very specific time). This is larger than the estimated annual 10^{-6} impact probability for unknown 2-km asteroids. The discovery and incorporation of observations from 1990 (*IAUC* 6839) immediately eliminated the possibility of an impact by 1997 XF$_{11}$ for several millennia. An object in a short-period orbit destined to strike the earth is likely to make other close approaches beforehand. Important lessons to learn from the 1997 XF$_{11}$ "fiasco" are that considerations of simple dynamics and geometry are at least as important as probabilistic estimates, and that there is a need to ensure that searches are made for prediscovery images and that an aggressive observational follow-up program is carried out for new NEO discoveries that may seem only an indirect threat.

The USNO SIM Grid Star Selection Program

B.D. Mason, T.E. Corbin, A.R. Hajian, C.A. Hummel, T.J. Rafferty, S.E. Urban, &
N. Zacharias (*USNO*) bdm@draco.usno.navy.mil

The United States Naval Observatory (USNO) is in the process of preparing an input catalog of SIM grid stars by utilizing existing databases, observing capabilities, and instrumental development. The SIM grid should be astrometrically stable at the 4 μas level over the five year life of the program, therefore, double and multiple stars must be avoided. Stars in the apparent magnitude range 6.5 $<$ m_v $<$ 8.5 with spectral types from A5V through G5V are being considered. Known doubles have been eliminated, and proper motions will identify previously unknown, wide pairs. This program involves a comprehensive selection and observing program, the first half year of which has seen candidate selection and the start of survey observations with the USNO speckle camera. In later years, further elimination of doubles will be made astrometrically with the Navy Prototype Optical Interferometer and wide-field CCD work. In addition, a Fourier Transform Spectrometer (FTS), with a potential for sub-meter per second radial velocity determinations, is being developed to eliminate companions (both stellar and substellar). In total, 7,200 candidate stars, evenly distributed over the sky will be examined observationally. The combination of the four astrometric methods will remove double and multiple systems in the $\sim$15 arcsec to $\sim$1 milliarcsecond range with Δm_v of 3.5 magnitudes, while the FTS is expected to detect companions with masses as low as Saturn in the range of 0.1 to 10 au. The first year of the program has thus far seen significant progress. The SIM grid candidate list has been prepared and speckle observations of these candidates have begun: in the northern hemisphere, by the USNO and the RIT/Yale group (Elliott Horch & Zoran Nikov, Rochester Institute of Technology and William van Altena, Yale).

Close Pairings of Galilean Satellites Observed Using Speckle Interferometry

B. D. Mason, G. H. Kaplan, G. G. Douglass, D. Pascu (*USNO*), &
K. Aksnes (*Institute for Theoretical Astrophysics, Oslo*) bdm@draco.usno.navy.mil

During November-December 1998, a series of events occurred involving the Galilean satellites of Jupiter, where two satellites (usually Io and Europa, but sometimes Europa and Ganymede) passed within 5 arcsec of each other. Depending on the orbital geometry and closest separation (as close as 2.9 arcsec) the events lasted anywhere from 20 minutes to several hours.

Since 5 arcsec roughly defines the atmospheric isoplanatic patch, attempts were made to observe these events using the speckle interferometry camera attached to the U.S. Naval Observatory (USNO) 26-inch refractor. The camera and associated software are normally used for precise measurements of the distance and position angle of binary star components. For the satellite events, the goal was to obtain very precise relative positions of the satellite pairs at specific times, as well as the time of apparent closest separation. Speckle observations of binary stars made from USNO typically yield positional accuracy of about 1

We successfully observed 4 out of a possible 8 events visible from USNO. Reduction of these observations is in progress. Despite the fact that the Galileans are resolved, not point sources, autocorrelations of the speckle patterns appear fairly strong. However, because of the relative motion of the satellites, only short integration times can be used, and it remains to be seen whether the signal-to-noise ratio will permit relative position measurements of useful precision.

Close pairings of the Galilean satellites occur in series that are determined by the mutual resonances, within a geometric envelope defined by the apparent inclination of the orbital planes (i.e., Jupiter's equator) and distance. There is another series of events in May-June 1999, then again in January 2000. This technique may also be applicable to some of the Saturnian satellites near the time of ring-plane crossing. We invite other speckle interferometry groups to attempt observations of these events so that the usefulness of the technique can be better determined.

Resonant Orbits in Triaxial Potentials

D. Merritt (*Rutgers University*) merritt@astro.rutgers.edu

Box orbits in triaxial potentials are generically *thin*, that is, they lie close in phase space to a resonant orbit satisfying a relation $l\omega_1 + m\omega_2 + n\omega_3 = 0$ between the three fundamental frequencies. The thickness of an orbit is limited by the condition that it avoid the destabilizing center of the potential; orbits that violate this condition are stochastic. The properties of thin box orbits in a family of triaxial potentials are discussed.

Trajectory Separations Revisited

R. H. Miller (*U. of Chicago*) rhm@oddjob.uchicago.edu

The gravitational $n-$body problem is chaotic. Consider two very similar $n-$body systems, each represented by a point in the same $6n-$dimensional phase space. The two points start very near each other, but they separate rapidly as the systems develop, resulting in phase trajectories that also separate rapidly. The rate looks exponential over long times. Such systems are extremely sensitive to initial conditions. At any instant, phase points separated in certain directions move apart (unstable directions), while those separated in other directions stay at about the same distance (stable directions). Unstable directions lie along eigenvectors of the matrix of force gradients that correspond to positive eigenvalues. The number of positive eigenvalues of that matrix gives the dimensionality of unstable subspace. This number changes extremely rapidly as a system moves through configuration space. On average, there are about $1.2n$ unstable directions out of $3n$.

Numerical effects augment the sensitivity, bringing their reliability into question. The issue whether numerical computations yield reliable estimates hinges on whether numerical systems populate the phase space in the same way as physical systems. "Shadowing" appears to hold some promise of assuring reliability, but it does not address the question how computed trajectories populate the phase space. In fact, it seems to say more about the character of chaotic trajectories: they are wilder than we'd imagined. For almost any computed trajectory, a segment of a physical trajectory can be found along which the physical phase point remains near the computed system's phase point for a surprisingly long time.

Estimates of the rate of trajectory separation require that the force gradient matrix be averaged somehow over realistic phase trajectories. Attempts to do this require lots of additional assumptions. This problem will be discussed, as will the question whether practitioners of the $n-$body art can safely be reassured by shadowing.

Status of the Second Guide Star Catalog

J. Morrison & B. McLean (*Space Telescope Science Institute*) morrison@stsci.edu

The second generation Guide Star catalog (GSC II) is being constructed at STScI in collaboration with Osservatorio Astronomico di Torino to support the operations of current and future ground and space based telescopes. This catalog will be an all-sky catalog of positions, proper motions, magnitudes and colors to the plate limit, however for operational purposes the goal is 18th magnitude.

The GSC-II is based on STScI digitized Schmidt survey plates from the modern POSS-II (J and F plates), ER, and SES surveys along with the older epoch POSS-I, Palomar Quick-V and UK Schmidt J and EJ surveys. The photometric reference catalogs used to calibrate the plates are the TYCHO catalogue and the second Guide Star Photometric Catalog (GSPC-II). The GSPC-II, an extension of the GSPC-I catalog, is comprised of CCD observations that will provide a set of standard stars to at least 18th magnitude over the entire sky for each Schmidt plate. The anticipated completion date for the GSPC-II catalog is the end of 1999. The final GSC-II catalog will be on the ICRF reference frame as represented by the USNO ACT catalog, however the majority of the plates processed thus far are on the PPM system.

The enormous amount data are organized in the COMPASS database. COMPASS, an object-oriented system with an estimated size at completion of 4 Tbytes, is structured for optimizing calibrations and supports consistent object naming between plates, as well as cross-matching with other optical surveys and with data from other wavebands. A much smaller ”export” catalog, in ESO SkyCat format, will also be produced. In this paper we represent the current status of the GSC-II catalog, emphasizing the astrometric and photometric calibrations.

On Computer Algebra Generation of Symplectic Integrator Methods

M.A. Murison (*U.S. Naval Observatory*) & J.E. Chambers (*Armagh Observatory*)

murison@aa.usno.navy.mil

Most symplectic integrators used in solar-system dynamics are second-order in the time step τ. Typically, the Hamiltonian is divided into a Keplerian piece H_A and a smaller perturbative component H_B. We can take advantage of the disparity in relative magnitude of these components to define a second small parameter, call it $\epsilon = \frac{|H_B|}{|H_A|} \ll 1$, and use this to obtain a 'partially' higher-order method.

Adopting a Lie series approach, one can, for a given order-N method, examine the τ^{N+1}, τ^{N+2}, etc. error terms. Each of the $2^k - 2$ subterms of the coefficient of the τ^k error term has an associated factor of ϵ raised to a power ranging from linear to $k-1$. By including adjustable parameters in each evolution operator $exp(\tau\{\cdot, H_A\})$ or $exp(\tau\{\cdot, H_B\})$ in the trial method (composed of a combination of these operators) that approximates the true Hamiltonian evolution operator $exp\left(\tau\{\cdot, H_A + H_B\}\right)$, one can in principle eliminate specified subterms in specified error terms. For example, a second-order method chosen to eliminate the τ^3 subterms linear in ϵ can, depending on the magnitude of ϵ, produce a quasi-third-order method. In practice this process boils down to generating then solving systems of nonlinear polynomial equations particular to the trial method.

A computer algebra program has been developed that automates the generation and solution of the equations that result from requesting a specified method of order N. This task is tedious due to the noncommutative algebra involved in the series expansions and subsequent algebraic manipulations, but computers are well-suited for handling such tedium. Once a method, or set of equivalent methods, has been found, the program then generates and solves a second set of equations for parameter solutions whereby subterms of specified powers in ϵ are eliminated for successive τ^{N+1}, τ^{N+2}, etc. terms in the overall error expression.

The project has, in these initial stages, been at least partially successful. Experiences and results to date will be presented.

Supernovae, Magnetic Fields, and Magnetars: Dynamical Interaction of a Magnetic Bubble with the Interstellar Medium

W.I. Newman (*University of California, Los Angeles*) &
A.L. Newman (*California State University, Dominguez Hills*) win@ucla.edu

Last year, Kouveliotou et al. (1998) discovered a new class of short-lived old stellar objects known as magnetars. When a massive star undergoes the catastrophic collapse which precedes a supernova explosion, it undergoes a very rapid spin-up causing its attached dipolar magnetic field lines to become very tightly wound in a toroidal configuration achieving strengths of 10^{15} Gauss or more. The corresponding Larmor radius is very small in contrast with the collisional mean free path, and a magnetically-driven collisionless shock of a $\beta = 0$ plasma (i.e., magnetic pressure much stronger than the thermal pressure) proceeds into the surrounding interstellar medium. In this paper, we explore the dynamical evolution of this magnetically-driven shock and its scaling properties. In addition, we explore the transition from an MHD-driven shock to a gas dynamical shock (the Sedov solution), as Ohmic dissipation ultimately converts the energy contained in the magnetic field into thermal energy.

The F ring: Saturn's crooked halo?

P. D. Nicholson (*Cornell University*), R. G. French (*Wellesley College*), &
A. S. Bosh (*Lowell Observatory*) pdn2@cornell.edu

HST observations of the ring-plane crossings in May, August and November 1995 showed that the edge-on brightness of Saturn's rings is dominated not by the classical A and B rings, but by the narrow, irregular F Ring (Nicholson *et al.,* [1996] *Science* **272**, 509; Bosh & Rivkin [1996] *Ibid* **272**, 518). Located 3500 km exterior to the outer edge of the A ring, and bounded by the small satellites Prometheus and Pandora, the F ring is ~ 50 km wide, optically thin at normal incidence angles, and exhibits a multi-stranded appearance in high resolution Voyager images (Murray *et al.* [1997] *Icarus* **129**, 304). Occultation observations in 1980/81 and 1989 show a single strand which is well-fitted by a precessing keplerian ellipse with semimajor axis 140209 km and $e = 0.0029$. A stellar occultation observed by HST on 22 November 1995, just after the solar ring plane crossing and at a terrestrial incidence angle of only 2.7 deg, revealed that the F ring is inclined at an angle of 0.0062 deg to the plane of the main rings (Olkin & Bosh [1996] *BAAS*, **28**, 1125). This non-zero inclination, which corresponds to a vertical amplitude a sin $i = 15$ km, also manifests itself in the partial eclipse of the F ring by the A ring in the November HST images. By precessing the ring back to the Earth ring plane crossing of 10 August, we find that the curious east-west asymmetry in the brightness of the main rings noted at this time - which is the principal source of uncertainty in the crossing time (Nicholson & French [1997] *BAAS* **29**, 1097) - is apparently due to partial obscuration of the A and B rings by the inclined F ring. By chance, the Earth crossing of 22 May occurred when the line of nodes pointed to the Earth, and no such asymmetry was seen. Photometric models of the edge-on ring brightness should permit us to determine both the thickness and radial optical depth of the F ring, and eventually to refine the ring plane crossing time to within an uncertainty of a few minutes.

The Large Scale Structures in the Outer Solar System: I. Cometary Belts With Resonant Features Associated With the Orbits of Four Giant Planets

L.M. Ozernoy (*George Mason U.*), N.N. Gorkavyi (*NRC/NAS & NASA Goddard*), &
T.A. Taidakova (*Crimean Astrophys. Obs.*) ozernoy@science.gmu.edu

By using a fast and efficient numerical approach, we simulate a stationary distribution of comets in the outer Solar System, where just a few representatives of the multi-million cometary population is currently known. These computations account for the major dynamical factors, such as gravitational scattering of comets on the four giant planets and effects of mean motion resonances. Our simulations allow to reconstruct, in the space of orbital coordinates, the distribution function for the population of minor bodies between Jupiter and Neptune and beyond. This makes it possible to compute the entire structure of the cometary populations between Jupiter and the Kuiper belt objects. In our simulations, we deal with 36 stationary distributions computed at different initial conditions for the dynamical evolution of comets, which start from the Kuiper belt and are usually traced until their ejection from the Solar system. These simulations include about 30×10^6 test bodies, which is comparable with the number of expected scattered comets (similar to Jupiter-family comets in their physical parameters). The simulations indicate that those comets are concentrated into four circumsolar belts, with a highly non-uniform and well structured distribution of the objects. Although the belts overlap, each belt can be associated with the orbit of the appropriate giant planet. This huge population is expected to have, as our simulations demonstrate, a rich resonant structure formed due to gravitational perturbations, i.e. in a non-dissipative way, and containing (i) gaps, (ii) diffusive accumulations, and (iii) near-resonance accumulations. It resembles resonant structures in the main asteroid belt, such as the Kirkwood gaps and the Hilda group. Our simulations allow for the foundation of a firm basis for observations of very distant cometary bodies, including Centaurs. Another important outcome is that the simulated cometary populations are the major source of dust in the outer Solar system. The distribution of dust from those sources could serve as a template for dusty disks in exo-planetary systems.

Astrometry and Orbits of the Inner Satellites of Neptune

D. Pascu, J.R. Rohde, P.K. Seidelmann (*USNO*), E.N. Wells, J.L. Hershey (*CSC/STScI*), B.H. Zellner (*GaSou*), A.D. Storrs (*STScI*), D.G. Currie (*UMd*), & A.S. Bosh (*Lowell*) pas@cygnus.usno.navy.mil

We have obtained 39 HST (PC2) images of Neptune, Triton and inner moons in three HST orbits: two on 3 July, one on 6 July 1997. Of the six inner satellites discovered by Voyager 2, the four outer ones were recovered, as expected, and near their ephemeris positions. The two inner satellites were too faint and close to the planet for detection.

The planet and all satellites were centroided with a Gaussian model using only the unsaturated portions of the images. The bright halo near the planet was also modelled for the faint satellites. The centroiding precision for Neptune and Triton was less than 1 mas, while that for the faintest satellites, embedded in the planetary halo, as high as 15 mas. After a correction for geometric distortion was applied, the scale and orientation were calibrated for each frame using the JPL ephemeris of Triton relative to Neptune. Two results of the astrometry were; a mean scale for PC2 of 0.045542 arcsec/pix, smaller by 1 part in 1900 than that determined from our astrometry in the Uranian system, and an orientation zero point correction dependent on the filter used.

In the orbital analysis, only corrections to the mean daily motions, given by Owen et al. (1991, AJ 101, 1511) for the four faint satellites, were made. Neptune was taken as the coordinate zero point, and separate solutions made in separation and position angle, as well as combined solutions. All mean motion corrections were well below the quoted mean errors of the starting values. The separation and position angle solutions were in agreement for the three faintest satellites, but were in disagreement for Proteus, despite the 6 mas mean residual after solution. The cause for this discrepancy is being investigated. The corrected mean motions, resulting from these observations, are expected to provide ephemeris predictions accurate to 100 mas throughout the next century.

Probing the Structure of the Galaxy with Microlensing

S. J. Peale (*UCSB*) peale@io.physics.ucsb.edu

The dependence of the analysis of detailed motions within our galaxy on the distribution of mass therein warrants the vigorous pursuit of a variety of observational techniques that constrain this distribution. Hardware and software developments have led to successful programs that have detected and cataloged more than 250 gravitational lensing events, involving stellar masses and called microlensing events for historical reasons, toward the center of the galaxy, and the data continues to accumulate at an ever increasing rate. This means that microlensing can be an effective probe of galactic structure and other properties in conjunction with other techniques when the data set is sufficiently large. The microlensing optical depth τ is the probability that a ray from a distant source will pass within the Einstein ring radius R_E of an intervening star (lens) on its way to the observer. The optical depth as a function of the direction of the line of sight is very sensitive to the distribution of stars in the galaxy—especially that in a bar-like bulge. This is demonstrated for variations of a particular galaxy model. The time scale of an event is defined as $t_E = R_E/v$ with v being the relative transverse velocity between the star being lensed (source) and the lens projected onto the lens plane, The distribution of time scale frequencies, the number of events per unit t_E as a function of t_E, depends on the mass function of the lenses, the distribution of both lenses and sources along the line of sight, and the circular velocities and velocity dispersions of the stars. Like the optical depth, the time scale frequency distributions are also sensitive to the line of sight directions. Both the optical depths and the time scale frequency distributions are routinely obtained from the growing data set. Although the dependence on so many parameters precludes definitive measures of any one galactic property by microlensing alone, constraint of some of these parameters with other techniques will allow powerful microlensing constraints on the distribution of stellar mass near the galactic plane. In particular, microlensing can detect late type dwarf stars that are invisible to all other techniques. In fact, the meager data set of about 50 events toward the galactic center that have so far been analyzed and published, imply far more M-type dwarfs than found in star counts. An empirical optical depth three times larger than that predicted from axisymmetric galactic models supports other evidence for a bar-like central bulge with the long axis pointing more or less toward the Sun. There may already be a sufficient number of events to constrain the distribution of stars in the galactic bar in considerably more detail. The variation of optical depth and time scale frequency distributions over an extensive range of parameter space defining galactic properties is demonstrated.

The U.S. Naval Observatory Pole-to-Pole Program

T.J. Rafferty & E.R. Holdenried (*U.S. Naval Observatory*) tjr@sicon.usno.navy.mil

Between the years 1985 and 1996 the U.S. Naval Observatory, using two transit circles, one located in Washington, DC (USA) and the other in Blenheim, New Zealand, conducted an ambitious program of fundamental observations of celestial positions completely covering both hemispheres. Over 735,000 individual observations were made, primarily of International References Stars (IRS), as well as all the major planets (except Pluto) and thirteen minor planets. Some 55,000 observations were obtained of day-time objects including the Sun, Mercury, Venus, and Mars. The original objective was to form a traditional, all-sky catalog of absolute star positions which could be firmly linked to the dynamical system. However, with the success of the Hipparcos project and the adoption of the ICRS as the celestial reference frame, the primary focus of the Pole-to-Pole program changed. The stellar positions have been differentially reduced to the system of Hipparcos and these were used to tie the planetary observations into the ICRS. Thus the program has resulted in a body of high quality observational data that will provide important input for modern, ICRS-based ephemerides. This is particularly true for the outer and minor planets.

Advanced Symplectic Integration of Collisional N-body Systems

K. P. Rauch & D. P. Hamilton (*Univ. Maryland*) rauch@astro.umd.edu

We examine the utility of several variations of the Kepler mapping of Wisdom & Holman (1991) combined with the potential-splitting modifications of Duncan, Levison & Lee (1998), which has shown great promise as an efficient, symplectic method for the integration of nearly-Keplerian systems undergoing dynamically-important close encounters. The relevance of factors such as coordinate system, use of symplectic correctors, and time-regularization are discussed. We have developed a new symplectic close encounter code incorporating these and other elements. We use the scattering of planetesimals by the giant planets to demonstrate the speed and versatility of our algorithms.

The Precession of a Spinning Spacecraft due to Radiation Pressure Torque

R. D. Reasenberg (*Center for Astrophysics*) reasenberg@cfa.harvard.edu

For a spacecraft with a large, nearly flat, optically uniform solar shield, the torque due to solar radiation pressure can be described simply. The FAME astrometric mission will use radiation pressure on such a shield, orthogonal to the nominal spin axis, to drive an Hipparcos-style observing pattern (Reasenberg and Phillips, SPIE 3356, 1998). The spacecraft, which has nominal periods of 20 min for rotation and 10 days for precession around the Sun direction, will be a precessing ”fast top.” FAME will measure 40 million stars with bright-star accuracy of 0.05 milli-arcsecond (mas). The full set of (six) first-order differential equations for the motions of the instrument axes may need to be integrated numerically to describe the motion to the required sub-mas accuracy. However, a useful understanding of the FAME rotation can be obtained by ignoring the Eulerian nutations and the (approximately zero) torque around the spin axis. One can then write a pair of first-order nonlinear differential equations for the motion of the angular momentum vector in a rotating coordinate system with the Sun along the x axis. These equations have been solved, ignoring the eccentricity of Earth’s orbit, as a series expansion in a small quantity proportional to the precession period (in years). The solution was confirmed and extended by multiple numerical integrations of the equations of motion. In the limit of fast precession, the motion around the Sun is circular and of uniform rate. As the precession period is increased, the first (and higher) order correction to the uniform circular path and the second (and higher) order correction to the period become important. For the FAME mission, these terms must be incorporated in the data analysis, but do not materially affect the quality of the observing schedule.

The Dynamical Evolution of the Earth-Moon Progenitors. II. Results and Interpretation

E. Rivera (*Dept. of Physics & Astronomy, SUNY Stony Brook*), J. J. Lissauer (*NASA Ames Research Center*), M. J. Duncan (*Dept. of Physics, Queen's University, Kingston ON*), & H. F. Levison (*SwRI*)

rivera@epimethius.arc.nasa.gov

Substantial evidence indicates that the Earth-Moon system formed about 100 Myr after the oldest meteorites and that the inner Solar System had five terrestrial planets for several tens of millions of years before the hypothesized Moon-forming impact. We present results from a series of N-body integrations in which the mass ratio of the Earth-Moon progenitors is 8:1, 4:1, or 1:1. We want to know if it is plausible that the Earth-Moon progenitors collided after 8 – 200 Myr, forming a system "similar to" the Solar System. If a collision occurs, the integrations tell us which two bodies collide and the time of the collision. We also determine the angular momentum deficit (AMD) of the resulting terrestrial planets. Additionally, we calculate several parameters of the collision.

We use the terrestrial planets' AMD to compare the resulting system to our own. The AMD of a planet is the difference between its orbital angular momentum and its orbital angular momentum were it in a circular orbit with zero inclination. The current AMD summed over the terrestrial planets varies between $\approx 7 \times 10^{44}$ g cm^{2}s^{-1} and $\approx 10^{45}$ g cm^{2}s^{-1} over the age of the Solar System.

We modified the SYMBA code to integrate our input systems and to calculate parameters of the impact if a collision occurs. Although most of our simulations result in a collision, in the majority of the runs the wrong bodies collide or the Earth-Moon progenitors collide too quickly after the start of a simulation. Some runs last 200 Myr without a collision or ejection. There are some simulations in which the Earth-Moon progenitors do collide 8 – 200 Myr after the runs start; a few of these are "similar to" the Solar System. Our results could be used as input for hydrodynamic simulations of the actual Moon-forming impact event.

FAME- Full-sky Astrometric Mapping Explorer

P.K. Seidelmann, M.E. Germain (*U S Naval Observatory*), T.P. Greene (*NASA Ames*), S.D. Horner, K.J. Johnston, D.G. Monet, M.A. Murison (*U S Naval Observatory*), J.D. Phillips R.D. Reasenberg (*Smithsonian Astrophysical Observatory*), & S.E. Urban (*U S Naval Observatory*) pks@usno.navy.mil

The Full-sky Astrometric Mapping Explorer (FAME) is a small satellite designed to perform an all-sky, astrometric survey with unprecedented accuracy. FAME will create an accurate astrometric catalog of ~40,000,000 stars with visual band magnitudes $5 < V < 15$. For bright stars, $5 < V < 9$, FAME will determine positions and parallaxes accurate to $<$ 50 microarcseconds, with proper motion errors $<$ 50 microarcseconds/year. For fainter stars, $9 < V < 15$, FAME will determine positions and parallaxes accurate to $<$ 300 microarcseconds, with proper motion errors $<$ 300 microarcseconds/year. FAME will also collect photometric data on these 40,000,000 stars in four Sloan DSS colors. FAME will map our quadrant of the galaxy out to 2 kpc from the Sun providing the information needed to calibrate the standard candles that define the extragalactic distance scale, calibrate the absolute luminosities of stars of all spectral types for studies of stellar structure and evolution, and detect orbital motions caused by brown dwarfs and giant planets. FAME will not only improve on accuracies of star positions determined by Hipparcos, but also expand the volume of space for which accurate positions are known by a factor of 8,000. FAME is currently in a NASA Midex concept study. FAME is a joint development effort of the U S Naval Observatory, the Smithsonian Astrophysical Observatory, the Infrared Processing and Analysis Center, Lockheed Martin Missiles and Space, the Naval Research Laboratory, and Omitron Incorporated.

Transient Spiral Patterns – Support from HIPPARCOS (invited paper)

J. A. Sellwood (*Rutgers University*) sellwood@astro.rutgers.edu

A long-standing controversy in theoretical studies of spiral structure has concerned the lifetimes of individual spiral patterns. Much theoretical work has sought quasi-stationary spiral modes while N-body simulations have consistently displayed recurrent, short-lived patterns. The simulations manifest a recurrent cycle of true instabilities related to small-scale features in the angular momentum distribution of particles, with the decay of each instability seeding the growth of the next. Data from the recent HIPPARCOS mission seem to offer support for the recurrent transient picture.

Interactions between Prometheus and the F Ring

M. R. Showalter (*Stanford*), L. Dones (*SwRI*), & J. J. Lissauer (*NASA Ames*)

showalter@ringside.arc.nasa.gov

Prometheus is the inner of the two "shepherding" moons straddling Saturn's F Ring, and is both larger and closer to the ring than its counterpart Pandora. It was found to be lagging its predicted orbital longitude by 19 degrees in 1995, and that lag has been increasing since. We are exploring a variety of possible interactions between the F Ring and Prometheus that could give rise to the observed orbital behavior.

(1) When Prometheus passes a sector of the ring, its gravitational perturbations generate periodic, short-lived clumps. If these clumps persist until the next passage of Prometheus 69 days later, the second passage can cause a segment of the ring to be "thrown" systematically to a higher or lower orbit. Because energy must be conserved, Prometheus should recoil slightly.

(2) The F Ring could easily contain a small number of as-yet undetected 1–5 km objects. The gravitational interaction of these bodies with Prometheus could introduce a small and apparently random component to Prometheus' motion.

(3) The orbital pericenters of the F Ring and Prometheus become anti-aligned (and therefore their radial separations are minimized) every 15–20 years. Shortly before the anti-alignment, Prometheus experiences a net positive tangential force from the ring, causing its mean motion to decrease slightly. Its mean motion returns to the initial value after the anti-alignment but the net effect is a small lag in longitude.

Our study involves a combination of analytic modeling and direct orbit integrations. Initial numerical simulations do show that the ring undergoes systematic changes in semimajor axis, which could in turn induce the expected recoil in Prometheus' orbit. However, the specific mechanism at work has not yet been determined.

Galaxy Clusters with Rounded Central Density Profiles

B.F. Smith (*NASA Ames Research Center*), & R.H. Miller (*University of Chicago*)

bfsmith@mail.arc.nasa.gov

Observational determinations of the mass distribution within galaxy clusters show that some clusters do not fit the density profile expected from hierarchical clustering of CDM material, which yields a sharp, cuspy center. Tyson *et al.* (1998) (*Ap.J.(Letters)*,Vol. **498**, pp. L107–L110) worked out the shape of the mass in the galaxy cluster $0024 + 1654$ by gravitational lensing. Happily, this cluster produces several gravitationally lensed images of the same background galaxy, and they used these images to solve for the shape of the mass in the cluster. Most of the mass is smoothly distributed throughout the cluster, although individual galaxies show up as sharp spikes atop that smooth background. An important feature of the background mass (which is most of the mass in the cluster) is that it is smoothly rounded at the center, which differs from expectations according to CDM. X-ray maps of many non-cD clusters also show rounded centers.

We are looking into other processes that might form clusters without cuspy centers. The first, and most obvious, process is to start from material with appreciable velocity dispersion. Systematic properties of clusters formed from these initial conditions are being studied: core radius, velocity dispersion, degree of central concentration, and the time required to reach a steady state, to list a few. Properties seem to scale with the ratio D/J, where D is the mean near neighbor distance and J is the Jeans length in the initial condition. Perhaps the most interesting property of these configurations is that they show long lived normal-mode oscillations. The present status of the investigation will be reported with emphasis on the character of the oscillatory modes.

Limitations of the Planetary Ephemerides

E. M. Standish (*Caltech / Jet Prop Lab*) ems@smyles.jpl.nasa.gov

The solar system may be regarded as the premier classical dynamical system of all time. It has been observed the longest; it is one of the most accurately measured; it is relatively clean - hardly any dust, friction, or static; and it has been undisturbed over the many years.

The ephemerides of the solar system have had many uses, often requiring the utmost accuracy: spacecraft navigation, reductions of observations, and testing of relativity and alternate theories of gravity.

There are, however, a couple of features which limit the ephemerides: perturbations from many asteroids whose masses are unknown, and friction between the lunar core and mantle. These features are described - their implications for the ephemerides, how they are handled during the ephemeris improvement process, and their resulting limitations upon the ephemeris accuracy.

A New Method for Simulating Gravitational Disk-Planet Interactions

G.R. Stewart (*Univ. of Colorado*) glen@artemis.colorado.edu

N-body simulations of the final stages of planet formation fail to form massive planets in the outer solar system unless a strong "drag" force is applied to damp the orbital eccentricites and inclinations of the largest planetesimals. A physical mechanism that could provide an effective drag is the excitation of collective gravitational waves in the disk of planetesimals. For example, Ward and Hahn (1998) have suggested that the planet Neptune could damp its orbital eccentricity by exciting apsidal waves in the Kuiper belt. I will describe a new numerical method for modeling the self-consistent dynamical interaction between a planet and an apsidal wave that can be inserted into an N-body simulation of planetary accretion. The most straight-forward method of simulating the wave would be to divide the disk into a collection of precessing wires that interact gravitationally with each other as well as with the planet. This is essentially the formalism described by Tremaine (1998) in his theory of "resonant relaxation." For linear waves, this method would require a large matrix multiplication each time step, where the dimension of the matrix is determined by the number of wires required to resolve the wave. A more efficient method is to approximate the solution of the wave equation with a truncated series of Chebyshev polynomials and use the collocation method to evaluate the gravitational interactions within the disk. Chebyshev polynomials are attractive because (1) they are eigenfunctions of the gravitational interaction operator for uniform density disks and (2) a much smaller number of polynomials (compared to wires) is required to resolve a given wave pattern in the disk. I will present the results of a simulation using the Chebyshev collocation method to model the dynamical evolution of a planet that is simultaneously excited by another planet and damped by an apsidal wave in the disk.

Uranus and Neptune: Fugitives from the Jupiter-Saturn zone?

E. W. Thommes, M. Duncan (*Queen's University*), & H. Levison (*SwRI*) thommes@astro.queensu.ca

Plantesimal accretion models of planet formation have been quite successful at reproducing the terrestrial region of the Solar System. However, in the outer Solar System these same models break down; without invoking other mechanisms, it becomes very difficult to grow bodies to the current mass of Uranus and Neptune. An alternative scenario to in-situ formation of these planets is explored here. In addition to the Jupiter and Saturn solid cores, several more bodies of mass $\sim 10M_{Earth}$ are likely to have formed in the region between 5 and $10AU$. If such bodies were subsequently scattered outward, dynamical friction with the protoplanetary disk would have acted to damp their initially high eccentricites and inclinations, and could have left some of them in circular, low-inclination orbits in the outer Solar System. Numerical simulations, using a code which fully models close encounters, show this scenario to be quite plausible for reasonable protoplanetary disk surface densities.

Searching for Extrasolar Planets with SIM

S. C. Unwin (*JPL/Caltech*) unwin@huey.jpl.nasa.gov

The Space Interferometry Mission (SIM) will be the first space-based long-baseline Michelson interferometer designed for precision astrometry. SIM will extend the reach of astrometry to cover the entire Galaxy, and will address a wide range of problems in Galactic structure and stellar astrophysics. It will also serve as a technology precursor for future astrophysics missions using interferometers. SIM will be a powerful tool for discovering planets around nearby stars, through detection of the reflex motion, and it will directly measure masses for the planets detected this way. It will have a single-measurement precision of 1 microarcsecond in a frame defined by nearby reference stars, enabling SIM to search for planets with masses as small as a few Earth masses around the nearest stars. More massive planets will be detectable to much larger distances.

The Yale/San Juan Southern Proper Motion Program

W. F. van Altena, T. M. Girard, I. Platais, V. Kozhurina-Platais, J. Ostheimer (*Yale Astronomy Department*), C. E. Lopez (*University of San Juan, Argentina*), & R. A. Mendez (*Cerro Tololo Interamerican Observatory*)
vanalten@astro.yale.edu

The SPM is based on photographic plates taken at our observatory at El Leoncito, Argentina and will yield absolute proper motions and positions to magnitude $B \sim 19$ for approximately 1 million stars south of declination -20 degrees. The SPM is a joint program between the Yale Southern Observatory and the Universidad Nacional de San Juan, Argentina. The SPM Catalog 2.0 provides positions, absolute proper motions, and photographic BV photometry for over 320,000 stars and galaxies. All objects contained in the SPM 1.0 Catalog (the South Galactic Pole region) are also included in this version. Note that SPM 1.0 has been replaced by SPM 1.1 which has slightly different astrometry (mostly proper motions) due to refinement of the magnitude equation correction in the SPM 2.0 Catalog. The Catalog covers an area of ~ 3700 square degrees in an irregularly bounded band between declinations of -43 and -22 degrees, but excluding fields in the plane of the Milky Way. Stars cover the magnitude range $5 < V < 18.5$. The standard errors for the best measured stars are as follows: 20 mas for positions in each coordinate; 2 mas/yr for absolute proper motions and 0.05 mag in B and V bandpasses. In addition to the Catalog, a list of CCD calibrating sequences in BV is provided. It contains 7783 stars. The new feature of the Catalog is an extensive list of cross-identifications with external special catalogs which include all major astrometric catalogs and a large number of astrophysically interesting objects. The Catalog is available on the WWW at http://www.astro.yale.edu/astrom/. Our web-site contains several useful plots showing the sky coverage, error distribution, a quick comparison with the Hipparcos proper motions, etc.

Orbital Structure of Rotating Triaxial Potentials

Valluri M. (*Rutgers University*) valluri@astro.rutgers.edu

The dependence of the orbital structure of triaxial galaxies on figure rotation is discussed. Rotation tends to increase the importance of stochasticity in the phase space of boxlike orbits.

Resonant periodic orbits in the three-body problem

F. Varadi (*UCLA*) varadi@ucla.edu

Periodic orbits in mean-motion resonances reveal a great deal about the dynamics of the three-body problem. The stable ones provide candidates for stable orbits in the more general N-body case of the actual Solar System. The unstable ones can explain the existence and extent of chaotic regions. This work employs a variety of techniques, such as the classical analytical continuation from the circular to the elliptic restricted three-body problem. Brute force searches are also carried out for cases which are not continuations from the circular case. The case of the general three-body problem is also studied.

Planetary orbits during the past 100 million years

F. Varadi (*UCLA*) varadi@ucla.edu

New numerical simulations of planetary orbits are carried out which take advantage of recent improvements in integration methods. In two integrations with slightly different step sizes, the difference in the low-pass filtered eccentricity of the Earth's orbit is less than one part in one million for the first 40 million years. After that, the exponential separation of orbits due to chaos dominates error growth. Preliminary results on the frequencies of secular motions indicate about one percent discrepancy as compared to earlier studies.

The first year of the UCAC-S project

N. Zacharias (*USNO / CTIO*), & S.E. Urban (*USNO*) nz@ctioj8.ctio.noao.edu

The US Naval Observatory CCD Astrograph Catalog South astrometric survey started in February 1998 at the Cerro Tololo site. By March 1999, 50% of the Southern Hemisphere was covered in a 2-fold overlap pattern, in a single bandpass (579-642 nm), using the 5-element 20cm aperture f/10 "red" lens and a Kodak 4k by 4k CCD. The goal is to produce accurate positions (20 mas for stars in the 8 to 14 mag range, 70 mas at 16 mag) on the Hipparcos system. It is planned to release some preliminary results from the first year of observing by mid 1999. Proper motions for stars brighter than V=12 will be derived by combining the UCAC positions with those in the Astrographic Catalogue and 160 other photographic and transit circle catalogs, all of which are reduced to the Hipparcos system. This work is also the basis for a collaboration with Copenhagen University Observatory to determine the proper motions of the stars in the upcoming Tycho-2 Catalogue, due out at the end of 1999. For stars fainter than V=12, the proper motions will be derived by combining the UCAC positions with those in the USNO A-2.0 catalog.