Session 1.
ORIGINS J.J. Lissauer, Chair

INVITED TALK - Migrating Planets

N. Murray (CITA, U. Toronto)

The discovery of roughly thirty extra solar planets over the last five years has profoundly altered our view of planet formation. The methods used to find the planets are sensitive to Jupiter mass bodies in orbits having periods less than about five years. With the caveat that the current searches are probably only marginally sensitive to systems like our own, the two main findings are that 1) Jupiter-mass planets are found in orbits with periods ranging down to three days, and 2) the distribution of orbital eccentricities is essentially uniform. The eccentricities show no obvious trends with planet mass or orbital period, aside from a lower limit on the orbit periapse that is consistent with expectations for tidal circularization. I will discuss theories for the origin of these "short period Jupiters". I will point out observational tests that might allow us to choose amongst the competing theories.

Stability of the Upsilon Andromedae System

E.J. Rivera (NASA Ames & SUNY Stony Brook), J.J. Lissauer (NASA Ames)

We present results of long-term numerical orbital integrations designed to test the stability of the three-planet system orbiting υ Andromedae. Our initial conditions are based on the latest fit to the radial velocity data obtained by the Marcy planet-search group at Lick Observatory. In comparison with the fit they presented last year (Butler et al. 1999, *ApJ* **526,** 916), the fit for the outer planet has significantly changed; the eccentricity has dropped from 0.36 to 0.31 and the period has increased from 1269 to 1319.7 days. Assuming that the middle planet is inclined by 1° with respect to the plane containing the other two bodies, we multiplied the planetary masses by some mass factor $m_f \equiv 1/\sin i$. An approximate analytic analysis of the star and the two outer planets shows that this subsystem is Hill stable for m_f up to 10 (note that this approximation is not very good for large m_f). Our integrations involving all three planets show that the system is typically stable for at least 5 Myr for $m_f \leq 5$. In comparison, our analysis using the initially announced observed orbital elements (Rivera & Lissauer 2000, *ApJ* **530,** 454), resulted in analogous systems which became unstable on time scales less than 1 Myr for $m_f > 2$. We observed a secular resonance between the outer two planets in both our previous and current analyses.

This research was supported in part by NASA's OSSRP under grant NAG 5-4640.

On Collective Behavior in a Planetesimal Disk.

W.R. Ward (Southwest Research Institute)

Recently there has been a renewed interest in the stability of a planetesimal disk against forms of collective particle behavior. For some time, it has been argued that gravitational instability is suppressed by turbulence at the gas-particle interface, which excites particle dispersion velocities and maintains the disk's Q above unity. However, the presence of a gas phase also introduces other modes of collective behavior by allowing the exchange of angular momentum with the gas reservior. These include both gravitational and non-gravitational modes, and can operate over longer wavelengths than the usual dynamic instabilities. We discuss the possibility that such long wavelength instabilites could decrease Q in regions of the disk, thereby triggering the onset of dynamic modes.

Tidal Interaction between a Planet and a Three-dimensional Gas Disk

H. Tanaka (SwRI, Tokyo Institute of Technology), T. Takeuchi (Stockholm Observatory), W.R. Ward (SwRI)

Tidal interaction with the solar nebula is effective for orbital evolution of planetary embryos in planet formation process. In most of studies of disk-planet interaction, the gas disk was assumed infinitesimally thin. We studied the tidal interaction between a planet and a three-dimensional isothermal gas disk, and evaluated the evolution rates of the orbital elements (i.e., semimajor axis, eccentricity, and inclination) by linear calculation. In our three-dimensional calculation, the excited density wave is expanded in Fourier series for the ϕ-axis of the cylindrical coordinates and it is further expanded with Hermite polynomials for z-axis.

Our result shows that the semimajor a, the eccentricity e, and the inclination i decrease due to the tidal interaction as well as the results of 2D calculation. For earth-mass planets at 1AU in the minimum mass nebula, the damping time-scales of a, e, and i are obtained as $1x10^5$, $4x10^2$, and $6x10^2$ years, respectively. These damping time-scales are inversely proportional to the planet mass and the disk surface density. This damping due to tidal interaction is more effective than that due to frictional gas drag for planetary embryos lager than $\sim 10^{24}$g.

Soft Drink Break - Poster Session

Heating of dust particles in radiative shock wave generated in protoplanetary disk

K.K. Tanaka (Dept. Earth & Planet. Sci., Tokyo Inst. Tech./LASP, U. Colorado), M. Horanyi (LASP, U. Colorado)

In formation stage of protoplanetary disk, shock waves are generated on the surface of the disk. As a result, dust particles existing in the infalling gas, as well as the gas itself, are heated by passing through the shock wave. In this study we investigated the shock heating of dust particles. A shock is composed of three regions: a preshock region, an intermediate thin region which is compressed adiabatically, and a post shock region. In the adiabatically compressed region, the gas temperature is very high ($>$ 6000 Kelvin), but the density is relatively low. In the post shock

region, the temperature decreases (to a few hundred Kelvin) with an increase in the density through the radiative cooling of gas and dust particles. We investigated the evolution of the temperature of the dust particles in these regions by solving the gas-dust coupled momentum and the energy equations.

The highest temperature of a dust particle is determined by the energy transfer between the gas and dust. We found that the heating rate of the dust particle in the adiabatically compressed region is smaller than it is in the post shock zone. In the post shock region, the temperature of a dust particle increases largely due to gas drag. We also find that the highest temperature of the dust particles, T_d, increases with decreasing the particle size, r_d, since the emissivity decreases for small dust particles. For example, T_d is 1600K for r_d=0.1 micron, while T_d is 1000K for r_d=1000 micron-sized dust in the case of that a shock wave generated in the asteroid region, where the gas velocity and density are 20 kms^{-1} and 1.2 $\times 10^{-14}$ gcm^{-3}, respectively.

Elemental Fractionation During Rapid Accretion of the Moon

K. Zahnle (NASA Ames), Y. Abe (Dept. of Earth and Planetary Physics, University of Tokyo, Japan), A. Hashimoto (Dept. of Earth and Planetary Sciences, Hokkaido University, Japan)

Chemical fractionation during the formation of the Moon from an impact-generated proto-lunar disk is investigated. The lunar forming material just before accretion is likely on the verge of vaporization. Hence, rapid accretion results in vaporization and formation of a transient silicate atmosphere on the Moon. The hydrodynamic escape of the atmosphere results in depletion of volatile and enrichment of refractory components on the Moon.

Oral Presentations:

The Rate of Chaotic Diffusion in the Interaction of Two Planets

G.R. Stewart (University of Colorado)

When a nonlinear oscillator is perturbed by a small amplitude, rapid frequency force, a narrow chaotic layer forms in the local neighborhood of the oscillator's separatrix. Alternatively, if the oscillator is perturbed by a large amplitude, slow frequency force, a broad chaotic sea fills the resonant region between the oscillator's pulsating separatrices. The two limiting cases are often called "fast chaos" and "slow chaos" respectively, because the rate of chaotic diffusion is very different in these two situations. In applications to celestial mechanics, fast chaos has been associated with overlapping mean motion resonances in the asteroid belt and slow chaos has been used to explain the chaotic evolution of planetary obliquities. I will present a model of resonant interaction between two planets that appears to simultaneously exhibit both fast and slow chaos. The model is a four-dimensional symplectic map which includes both a mean motion resonance and a secular resonant interaction. After an appropriate coordinate transformation, the model can be divided into a fast oscillator and a slow oscillator that are dynamically coupled. The fast oscillator remains in the thin chaotic layer near its separatrix and slowly forces the slow oscillator. The slow oscillator exhibits an adiabatic "invariant" that occasionally jumps as the trajectory crosses a slowly pulsating separatrix. Interestingly, one can derive analytic expressions for the rates of fast and slow diffusion for this model.

Stirring Rate of Planetesimals Based on Three-Body Orbital Integrations

K. Ohtsuki, G.R. Stewart (U. Colorado), S. Ida (Tokyo Inst. Tech.)

In order to study the early stages of planetary accretion from a very large number of planetesimals, numerical simulations based on the techniques of the kinetic theory of gases are generally used. In these simulations, the evolution of size distributions is calculated according to the collision rate, which depends on the mean eccentricity and inclination of planetesimals. Recently, an evolution equation for mean square eccentricity and inclination has been derived for particles with the Rayleigh distribution of eccentricities and inclinations (Ohtsuki 1999, Icarus 137, 152; Stewart and Ida 2000, Icarus 143, 28). Stewart and Ida (2000) obtained analytic formulas for the stirring and dynamical friction rates of planetesimals appearing in this equation and compared the velocity evolution with N-body simulations. They found fairly good agreement, but the following discrepancies remained unexplained: (i) Evolution in the low velocity cases disagree with N-body simulations. (ii) The dynamical friction terms in the analytic formulas have to be reduced by 30% to obtain agreement with N-body simulations. In order to clarify the reason for the above discrepancies and obtain more accurate formulas for the stirring rates, we calculated the stirring and dynamical friction rates of planetesimals with the Rayleigh distribution of eccentricities and inclinations by three-body orbital integrations using the method described in Ohtsuki (1999), who calculated these rates for ring particles. We have found excellent agreement of the velocity evolution calculated by the present results based on three-body orbital integrations with N-body simulations, for both one- and two-size component systems. The newly obtained stirring and dynamical friction rates can be used to derive revised analytic formulas for these rates, which can be used to produce more accurate numerical simulations of planetesimal accumulation.

The Good, the Bad and the Ugly: Assessing the Results of Planetary Accretion Simulations

J.E. Chambers (NASA Ames Research Center/NRC/Armagh Observatory), J.J. Lissauer(NASA Ames Research Center)

Here I present results of 16 new N-body simulations of the accretion of the inner planets. These calculations follow the dynamical and collisional evolution of a disk of planetary embryos to the point at which they form a stable system of terrestrial planets. The simulations differ from earlier N-body integrations by Chambers & Wetherill (1998, Icarus, 136, 304) and Agnor et al. (1999, Icarus, 142, 219) by increasing the initial number of embryos to about 150, and by using a wider range of initial masses.

At first sight, the planetary systems produced by the new integrations more closely resemble the terrestrial planets than the results of earlier simulations. However, there are still obvious differences, notably in the orbital eccentricities and inclinations, in the obliquities, and in the distribution of mass within the terrestrial-planet region.

To assess the results of these simulations, I propose a set of statistics to quantify some important characteristics of any system of terrestrial planets. The statistics allow us to see where the inner planets of the Solar System lie within the spectrum of computer-generated systems. In addition, we can see whether changes in the initial conditions used by the calculations are systematically narrowing the gap between simulation and reality.

Preliminary results suggest that increasing the initial number of embryos, and using a wider range of initial masses, may eventually solve the eccentricity and inclination problems. However, these changes do nothing to help reproduce the unusual obliquities of the terrestrial planets, nor explain why almost all of the mass in the inner Solar System is concentrated in the narrow range of semi-major axes occupied by Venus and Earth. This research was supported by the NRC, DENI, PPARC and Starlink.

The Role of Giant Planets in Terrestrial Planet Formation

H.F. Levison (SwRI), M.J. Duncan(Queen's U.), C.B. Agnor (U. Colorado)

The dynamical structure of the outer planetary system has played a critical role in determining the sizes, numbers, and habitability of the terrestrial planets. In 1996, Wetherill showed that the presence of Jupiter affects the masses of planets in the Habitable Zone of the Sun. In addition, in our solar system the giant planets control the dynamics of most of Earth's impactors, which consist of objects from the asteroid belt, the Kuiper belt, the scattered comet disk, and the Oort cloud. At early times, these impactors may have been responsible for supplying the Earth with a significant fraction of its water, organics, and atmospheric volatiles. At later times, they are responsible for causing at least some mass extinctions.

Recent observations have demonstrated that giant planet configurations can show startling variations from system to system. (Although the searches for extra-solar planets have yet to reveal anything about what 'typical systems' are like due to strong observational biases.) The question therefore naturally arises: What kind of outer planetary systems can support habitable terrestrial planets? The Exobiology Program is funding us to undertake the first comprehensive study of the coupling between outer solar system architectures and inner solar system habitability. The first stage of this program was to construct a wide range of outer planetary systems. The results of this work can be found at www.boulder.swri.edu/~hal/diversity.html. Here we present a preliminary report on simulations of the formation of terrestrial planets in two of these synthetic outer planetary systems. The first contains 5 planets; three of which lie between 3.7 and 11AU and have a combined mass of 2600 Earth-masses ($\sim$ 8 Jupiter-masses). The second system contains 7 planets between 4 and 35AU; the largest of which is only 26 Earth-masses ($\sim$ 1.5 Neptune masses).

Planet Migration Via Numerous Stochastic Scattering Events

J.M. Hahn, R. Malhotra (Lunar and Planetary Institute)

Gravitational scattering of a planetesimal disk by recently-formed giant planets may have caused a significant readjustment of planetary orbits. Indeed, an early epoch of planet-migration is often invoked to explain the resonant structure observed in the Kuiper Belt. Had Neptune's orbit smoothly expanded outwards about 7 AU, its 3:2 mean-motion resonance would have swept across much of the early Belt, simultaneously capturing Kuiper Belt Objects (KBOs) and exciting their eccentricities (Malhotra 1993, 1995).

However it should be recognized that planet-migration via gravitational scattering is a s-tochastic process. To effect this in our planet-migration simulations we add some random jitter to the torque that drives Neptune's outward expansion. This jitter is parameterized by σ, which is the standard-deviation of the planet-migration torque in units of the time-averaged torque. Larger σ increases Neptune's to-and-fro motion as its orbit expands.

We are investigating whether this jitter can account for the e and i excitation observed in the Kuiper Belt. A system of four migrating giant-planets plus numerous massless KBOs has been evolved for various values of σ. We find that the Kuiper Belt's resonance structure can be preserved despite a surprisingly large amount of jitter. For instance, simulations with $0 \lesssim \sigma \lesssim 10$ are largely indistinct due to the very efficient capture of KBOs at resonances. However runs with larger jitter, $25 \lesssim \sigma \lesssim 75$, have reduced capture efficiencies. This allows for the development of a stirred up 'classical disk' as particles have their eccentricities pumped up as they slip through the 2:1 resonance. Substantial inclinations of $i \sim 10°$ are also excited at the 3:2 resonance. Although a higher jitter of $\sigma \simeq 100$ results in a Kuiper Belt that is depleted interior to $a \simeq 45$ AU, inefficient capture still occurs at Neptune's 2:1 resonance. Further comparisons between model and observed endstates will be presented at conference time.

Implications of a scattered Uranus and Neptune

E.W. Thommes, M.J. Duncan (Queen's University, Kingston, Ontario), H.F. Levison (Southwest Research Institute, Boulder, CO), J.E. Chambers (Armagh Observatory, N. Ireland)

It has been proposed that Uranus and Neptune originated interior to $\sim 10AU$, as potential gas giant cores which were scattered outward when Jupiter won the race to reach runaway gas accretion (Thommes, Duncan and Levison, Nature 402, 1999). We report on further investigations into various aspects of this model. The dependence of the final locations of the giant planets on the heliocentric distance at which Jupiter undergoes runaway gas accretion is examined. Also, we find that the appearance of the inner Solar System can be significantly affected by both Jupiter and Saturn's range of migration to their final positions, since this determines the distances through which their resonances sweep. Another effect our simulations show is that cores tend to briefly penetrate the region of the outer asteroid belt in the process of getting scattered. In the majority of cases, the crossing duration is only a few 10^3 years, so that there is only modest excitation and depletion of the belt. However, in some circumstances, it is possible for a giant planet core to be deposited in a stable orbit interior to Jupiter. Conceivably, such an occurrence could have played a role in the formation of some of the discovered extrasolar systems.

Orbital evolution of KBOs due to the sweeping secular resonances

M. Nagasawa, S. Ida (Tokyo Inst. of Tech.)

We have investigated excitations of orbital eccentricity and inclination of Kuiper Belt objects (KBOs) caused by the sweeping secular resonances during the primitive solar nebula depletion. Root mean square of the inclination and eccentricity are about 0.23 (radian) and 0.1 in the outer (classical) Kuiper Belt (the region beyond 42 AU). These large values are not explained by present planetary perturbations alone. Although many studies were done to explain the origin of these large values, the origin of the large inclination is not well known yet.

We consider the sweeping secular resonances as the excitation mechanism. Four Jovian planets in the present configuration, seven secular resonances exist beyond the location of Neptune. When the solar nebula existed, the nebula potential would have significantly altered locations of the secular resonances. As the nebula was depleted, the secular resonances moved from their initial locations to the present ones, pumping up the eccentricity and the inclination of field bodies. We have investigated the effects of the sweeping secular resonances in KBOs with both direct orbital integration and analytical method, following Nagasawa et al. (2000, AJ, in press), which studied the sweeping secular resonances in the asteroid belt. For the initial nebula model, we basically employed the minimum mass solar nebula model extending to 150AU.

We found that the inclination of the bodies in the outer belt is excited to the observational level if the nebula density uniformly decreases from 1/5 to 1/1000 of the initial nebula in a timescale of $10^8 - 10^9$ years. The inclination of KBO is more excited easier than the eccentricity, which is consistent with observed orbital elements in the outer belt. This is because the resonances to pump up inclination migrate slower than the eccentricity's resonances do in the outer belt.

Session 2.
SOLAR SYSTEM DYNAMICS M. Showalter, Chair

INVITED TALK - Origin of the Moon

Robin M. Canup (Southwest Research Institute)

Several works have modeled lunar accretion from an impact-generated disk utilizing N-body orbital integrations. These simulations have described the initial protolunar disk with $N = 10^3$ to 10^4 100-km sized moonlets. Typically after $\sim 10^3$ orbits (about a year), one large moon has accreted just outside the Earth's Roche limit with a mass that is a function of the initial disk angular momentum.

While past models have been successful in yielding a single moon, they have not provided an adequate treatment of the Roche-interior disk. Such a disk would contain vastly larger numbers of bodies than can be tracked using direct N-body techniques. In addition, the rate of disk spreading observed in the N-body simulations is so fast ($\sim$ a month) that it implies an energy release rate sufficient to vaporize the disk material. A more physically plausible model involves a disk viscosity (and lifetime) that is regulated by the disk's cooling time, $\sim$ 10-100 years. To address these issues, a "hybrid" model for lunar accretion is being developed that treats the Roche interior disk as a fluid with a radiation-limited viscosity, while Roche exterior material is still followed using an N-body approach.

If the inner disk persisted after the Moon formed, disk-Moon interactions would affect the Moon's early orbit. Indeed, it has recently been proposed that a single resonant interaction between a lunar-sized moon and an inner disk can increase the moon's orbital inclination to values as high as 15 degrees. This may offer an explanation for the origin of the Moon's puzzling initial inclination (which from the Moon's current orbit is known to have been about 10 degrees), and may remove an often-raised objection to the impact theory for lunar origin.

This work has been supported by the NASA Origins of Solar System and Planetary Geology and Geophysics Programs.

Numerical Integration, Lyapunov Exponents and the Outer Solar System

W.I. Newman, F. Varadi, A.Y Lee, W.M. Kaula (UCLA), K.R. Grazier (JPL/Caltech), J.M. Hyman (Los Alamos National Laboratory)

We determined analytically the dependence of the Lyapunov exponent upon time step for the linear paradigms of the simple harmonic oscillator (center) and simple repeller (homoclinic point) for several popular symplectic integration schemes. For the oscillator, we showed that there is a Hopf bifurcation resulting in the appearance of a non-zero Lyapunov exponent for sufficiently large step size, while the repeller produced a positive Lyapunov exponent for any step size. We explored the standard map, corresponding to integration of the pendulum problem, and showed how the Lyapunov exponent manifests similar behavior except that nonlinearity further reduces the value of the maximum time step that can be safely used before non-physical behavior manifests ($\approx 1/10$ period).

Recently, Grazier *et al.* (1999. *Icarus* **140**, 341–352) published the results of outer solar system planetesimal simulations that used an error-optimized modified 13$^{\text{th}}$ order Störmer integration scheme with a 4-day time step. Their computation showed no evidence for chaotic behavior among the four outer planets and the sun over an 8×10^8 year period for eight randomly selected initial conditions taken over a 300 year time span from the DE245 ephemeris. Using a second-order Wisdom-Holman integrator, optimized to minimize round-off effects, and the commonly used 400 day time step, we recovered the commonly cited exponential growth consistent with a Lyapunov time scale between 5 My and 12 My. However, when we reduced the time step to 200 days, the behavior is no longer demonstrably chaotic. A further reduction to 100 days in the time step shows no chaotic behavior over a 100 My period, and a 50 day time step based computation shows that the Wisdom-Holman calculation has effectively converged to non-chaotic behavior.

A Numerical Examination of the Long-Term Coherency of Meteoroid Streams in Near-Earth Orbit

K.R. Grazier (JPL/Caltech), M.E. Lipschutz (Purdue University)

The statement that some small bodies in the Solar System–asteroids, comets, meteors (of cometary origin)–travel in co-orbital streams, would be accepted by planetary scientists without argument. After all, streams have been observed of fragments of at least one comet (Scotti and Melosh, 1993; Weaver et al., 1993), asteroids (Drummond, 1991; Rabinowitz et al., 1993; Binzel and Xu, 1993) and meteoroids of asteroidal origin, like Innisfree (Halliday et al., 1990; cf. Drummond, 1991). Whether members of a stream can be recognized from compositional studies of meteorites recovered on Earth and linked to a common source is more controversial since such linkage would imply variations in the Earth's sampling of extraterrestrial material that persist for tens of Myr.

The dates of fall of H chondrites show that many - including Clusters in May, 1855-1895, September, 1812-1831 and Sept.-Oct., 1843-1992 – apparently derive from specific meteoroids (Lipschutz et al., 1997). Contents of highly volatile elements in these 3 Clusters (selected by one criterion, fall circumstances), when analyzed using multivariate statistical techniques demonstrate that members of each Cluster (i.e. stream) are recognizable by a totally different characteristic criterion: a thermal history distinguishable from those of random H chondrite falls (cf. Lipschutz et al., 1997, for specific references). Antarctic H chondrites with terrestrial ages 50 Myr (Michlovich et al., 1995) also show this. Metallographic and thermoluminescence data for these H chondrites also reflect their thermal histories, and support the existence of such meteoroid streams (Sears et al., 1991; Benoit and Sears, 1993), but cosmogenic noble gas contents do not (Loeken et al., 1993; Schultz and Weber, 1996). Important unanswered orbital dynamic questions are how long a meteoroid stream should be recognizable and what dynamic conditions are implied by Clusters, whose members have cosmic ray exposure ages of some Myr.

To begin to address these open issues, we simulate the trajectories of several near-Earth meteoroid streams–some with orbital elements corresponding to suspected streams, others randomly chosen. To integrate the trajectories as accurately as possible, we use an error-optimized modified 13^{th} order Störmer integration scheme, capable of handling close planet/meteoroid approaches (Grazier et al., 1998). Using Drummond's (1979) d' criteria to determine stream membership and coherency as a function of time, we find that stream coherency beyond 100 Ky–certainly beyond 1 My–exists but is rare.

Long-term Integrations of the Solar System

Ferenc Varadi (UCLA)

While long-term numerical integrations of the outer Solar System have become routine, the inner planets have received much less attention. The present work uses physical models of increasing complexity, which include General Relativistic and Earth-Moon tidal corrections. Even small modifications in the physical model can lead to changes in orbits over a few million years that are larger than what could be attributed to chaos. Comparisons between different physical models and also with previous results indicate that more integrations with accurate models are necessary to better constrain Earth's orbit for the past few tens of millions of years. Chaos in the inner Solar System has the largest effects on Mars, with clearly observable transitions between different types of dynamical behavior.

The Stability of the Terrestrial Planets in Systems with a Planet in the Asteroid Belt

E.V. Quintana (NASA Ames & University of Michigan, Ann Arbor), E.J. Rivera (NASA Ames & SUNY Stony Brook), J.J. Lissauer (NASA Ames), M.J. Duncan (Queen's University)

If a massive planetary-sized body was present in the asteroid belt, the orbits of the terrestrial planets and those of the giant planets would be more closely coupled. A greater exchange in angular momentum could affect the stability of the terrestrial planets. To study this effect, we have simulated several systems consisting of the solar system planets and a planetary-sized (0.1-10 Earth masses) asteroid in the asteroid belt. An integration with Ceres at five Earth-masses remained stable for a billion years. Runs with Ceres at ten Earth masses, however, caused the system to become unstable at $\sim$ 25-50 million years. When additional mass was given to both Ceres (bringing it up to five Earth masses) and Mars (one Earth mass), the systems remained stable for a comparable amount of time. A system with Pallas at five Earth masses became unstable at 170 million years. Vesta at five Earth masses, however, caused the system to become unstable in less than 100 million years. This research was supported in part by NASA's OSSRP under grant NAG 5-4640.

Coffee Break - Poster Session

The Determination of the Orbits of the Outer Jovian Satellites

R.A. Jacobson (JPL/Caltech)

The eight outer satellites of Jupiter may be divided into two groups of four. Those in the first group, Himalia, Elara, Lysithea, and Leda, are in high inclination direct orbits between 11 and 12 million km from Jupiter. Those in the second group, Pasiphae, Sinope, Carme, and Ananke, are in high inclination retrograde orbits between 20 and 24 million km from Jupiter. Rocher and Chapront (1996 *A&A* **311**, 710) have published orbits for Himalia, Elara, Pasiphae, and Sinope fit to observations from their discoveries through 1993. Apparently, only Herget (1968 *AJ*, **73**,

737) has published orbits for Lysithea, Carme, and Ananke. These were later extended by Aksnes (1973 *AJ*, **78**, 121) who also determined an orbit for Leda (1978 *AJ*, **83**, 1249).

To support the Galileo Project, I fit numerical integrations of all eight satellites to observations from their discoveries through 1994. I have extended the fit to include observations through January 2000. Among the additional observations are highly accurate CCD measurements obtained at both the US Naval Observatory, Flagstaff Station (Stone & Harris, to appear in AJ), and JPL's Table Mountain Observatory (Owen, private communication). The table below gives the number of observations of each satellite and the root-mean-square (rms) of the post-fit residuals.

Observation Residual Statistics - rms

Timespan	Satellite	No.	$\Delta\alpha \cos\delta$	No.	$\Delta\delta$
1894-2000	Himalia	736	$1''.18$	737	$0''.92$
1905-2000	Elara	345	$0''.95$	345	$0''.82$
1908-2000	Pasiphae	472	$1''.13$	472	$0''.89$
1914-1998	Sinope	210	$1''.19$	210	$0''.98$
1938-1998	Lysithea	124	$0''.75$	124	$0''.72$
1938-1998	Carme	145	$1''.01$	145	$0''.81$
1951-1998	Ananke	134	$0''.88$	134	$0''.88$
1974-1998	Leda	67	$0''.87$	67	$0''.70$

The current integration includes perturbations due to the Sun, Saturn, the Galilean satellites, and the oblateness (J2 only) of Jupiter. The masses of Jupiter and the perturbing satellites and the Jupiter J2 are from the Galileo data analysis.

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

The Fate of Ejecta from Hyperion

A.R. Dobrovolskis (University of California at Santa Cruz), J.J. Lissauer (NASA Ames Research Center)

Material ejected from Saturn's moon Hyperion is subject to powerful perturbations from nearby Titan, which control its ultimate fate. We have used the SWIFT symplectic integrator package of Duncan and Levison to simulate a simplified system consisting of Saturn (including J2 and J4), Titan, Hyperion, Iapetus, and the Sun (treated simply as a massive satellite). This model correctly reproduces the libration amplitude of the 4:3 resonance between Titan and Hyperion. In addition, 210 massless particles, more or less evenly distributed over latitude and longitude, were ejected radially outward from 1 km above the mean radius of Hyperion at 10% faster than its escape speed. Titan accretes most such particles within a few thousand years, while only about 17% survive for as long as 40,000 years. One particle hit Saturn, while another escaped the Saturn system, but Hyperion reaccreted only a few percent over this time. This may help to account for Hyperion's rugged shape.

Conversely, because Hyperion regularly makes relatively close approaches to Titan's Lagrange points L4 and L5 (and L3), Colombo, Franklin, and Shapiro (A.J. 79, 61-72, 1974) speculated that Titan cannot retain Trojan companions. However, our integrations also show that Titan (and Iapetus) can maintain a wide range of Trojan, tadpole, and horseshoe-type coorbitals, at least for 1000 years. In contrast, Hyperion itself can have only horseshoe companions over this time, because of perturbations from Titan. The long-term stability of coorbitals in this system is still open to question.

Oral Presentations:

Asteroid Noise in the Motions of the Inner Planets

M.A. Murison (U.S. Naval Observatory)

The major planets plus all known asteroids of diameter 70 km or greater were numerically integrated for 500 years in a detailed study of the short-term effects of the asteroids - viewed as a noise source - on the orbital motions of the inner planets. Preliminary results are presented. Asteroid perturbations cause the planetary semimajor axes to oscillate (with the exception of that of Mercury, which drifts) and the other orbital elements to exhibit secular drifts. Short-period perturbations in semimajor axis range in amplitude from less than 0.5 m for Mercury to 200-300 m for Mars. Power spectra exhibit a forest of individual spectral lines with an underlying noise floor. Real power exists at all frequencies, roughly 2-4 orders of magnitude below the spectral peaks. The effects of a single massive asteroid are qualitatively the same, but with fewer individual spectral lines. Quantitatively, the noise floor drops by an order of magnitude and appears to scale linearly with the total asteroid mass. The shape of the noise distribution is discussed.

Dynamical Evolution of Main-Belt Meteoroids: Numerical Simulations Incorporating Planetary Perturbations and Yarkovsky Drag

J.A. Burns, W.F. Bottke (Cornell University), D.P. Rubincam (NASA-Goddard)

Using an RMVS N-body integrator, we track meteoroid orbital histories, including planetary perturbations plus the Yarkovsky (radiation-recoil) effect (seasonal and diurnal variants, producing orbital collapse or growth, depending on meteoroid properties and spin); collisions stochastically alter spin rates and directions. Considering two drift rates, we follow – for tens of Myr – one hundred bodies started from the positions of each of ten asteroids (e.g., Vesta, Hebe, Maria, Flora, Hestia) scattered across the inner main belt. This region contains the powerful Jovian 3:1 mean-motion resonance and the ν_6 secular resonance, as well as numerous weaker three-body (Jupiter, Saturn, meteoroid) and Martian mean-motion resonances. Once modest eccentricities are achieved, orbits can pass near Mars, which significantly affects them.

Dynamical evolution in the main belt can be quite complex. Depending on the speed and direction of orbital evolution as well as the particular resonance, particles may i) be captured, increasing e and/or i while a stays constant; or ii) jump across, kicking e, i and a, but bypassing potential "escape hatches" from the main belt. Chaos ensues once resonances overlap.

Following convoluted trajectories, which vary with initial conditions and collisional histories, most meteoroids reach Earth-crossing orbits via the 3:1 or ν_6 resonance after tens of Myr in the main belt. These timescales correspond well to the measured cosmic-ray-exposure ages of chondrites and achondrites. Meteorite source are, however, less clear; since Yarkovsky drift allows access to a dense forest of resonant sites, nearly any body in the main belt can add to the cumulate meteoroid flux. Ejecta from small parent bodies will dominate the meteoroid flux if the main- belt size-distribution at sub-km sizes is in collisional equilibrium, while big parent bodies dominate if observed population trends for km-sized bodies persist to smaller radii.

The Puzzle of the Titan-Hyperion 4:3 Orbital Resonance

M.H. Lee, S.J. Peale (Dept. of Physics, UCSB)

A tidal origin of the 4:3 mean-motion resonance of Saturn's satellites Titan and Hyperion suffers from the requirement that the dissipation parameter Q of Saturn for Titan induced tides must be much smaller than the minimum effective Q established for Mimas induced tides. An alternative scenario is that Hyperion formed by the accretion of satellitesimals at the resonance. We investigate the viability of this alternative scenario by using the symplectic integrator SyMBA to simulate the accretion of satellitesimals in the Hyperion region of phase space. N-body simulations with $N \approx 1000$ particles initially, different imposed rates of growth of Titan's mass and eccentricity, and different initial total satellitesimal masses are performed. *Preliminary* results indicate: 1. The interaction among the satellitesimals is sufficiently strong that the accretion process is not significantly affected by the presence of the mean-motion resonances with Titan. In particular, there is preference for the particles to grow outside the resonances rather than within them. Although several particles are trapped in each of several resonances, there appears to be no significant coagulation of these resonant particles — a result that may be due to the restriction to non-crossing orbits due to the phasing within the resonance. 2. Gas drag is added to some of the calculations, but it is sufficiently weak that it has little effect on the accretion of particles. If the drag persists, the accreted particles will decay to and be trapped within the first strong resonance encountered at smaller semimajor axes. 3. The accretion timescale is sufficiently short that 1–3 large embryos of masses comparable to current Hyperion mass can be formed in less than 10^6 Titan periods, but in all cases there are no large embryos at the 4:3 resonance — large embryos near the 3:2 resonance being preferred. The sometime expressed assumption that accretion is enhanced near orbital resonances is so far not supported by these simulations. Hyperion is not going to yield the secret of its history easily.

Detection of a Europan Ocean from Tides and Rotation

C.F. Yoder (Jet Propulsion Laboratory)

Europa's icy surface displays tectonic evidence of thin shell (<20km) dynamics while the predicted total depth of the ice-water layer is 80-140km from moment of inertia. Jupiter raises 20-30m periodic tide resulting from orbit eccentricity. This 3.55d tide can be detected from an orbiting spacecraft using altimetry (which measures Love number h_2 and Doppler tracking (which observes the gravimetric k_2 Love number). Measurement of both Love numbers first establishes the existence/absence of a global water ocean and second determines the relative deformation of ice shell and mantle. Shell tidal amplitude constrains the product of the mean shell depth $d_4 R$ times rigidity μ_4. Solid ice $\mu_4 = 4x10^{10}$ dyne-cm might be reduced by fractures and partial melt. Jupiter also drives an axial oscillation of Europa's figure which is proportional to $e \sin M$ where M is the orbital mean anomaly. This rotation amplitude is sensitive to whether the ice shell is grounded or floats free. The predicted solid body rotation amplitude is 140m at the equator while the predicted amplitude for a 'deep ocean' (> 10km) is <85m. The most interesting feature of decoupled motion is that shell libration amplitude is dependent on shell rigidity and less so on thickness. Thus, precise measurement of this amplitude along with the above tidal signatures determines both shell thickness and rigidity. This abstract presents the results of one phase of research carried out at the Jet Propulsion Laboratory, CalTech under contract with NASA.

INVITED TALK - Resonances, Drag Forces and the Jacobi Constant

D.P. Hamilton (University of Maryland)

Resonances are fundamental in orbital dynamics, and are responsible for a diverse set of Solar System phenomena including gaps, density waves, and bending waves in Saturn's rings; asteroids and satellites on tadpole and horseshoe orbits; gaps and enhancements in the asteroid belt and the delivery of meteoroids to Earth; tidal heating and volcanism on Io; the broad and dusty Saturnian E-ring; stable longitudes in the geopotential; the large vertical extent of the Jovian ring's diffuse halo; the high orbital eccentricities of Pluto and some Kuiper Belt objects; spin-locking of planetary satellites; and the dusty ring exterior to Earth's orbit.

The Solar System did not form in its current resonant-rich state though, rather it evolved slowly into this state under the influence of drag forces including planetary tides, planetary migration, Poynting-Robertson drag, plasma drag, and nebular drag. All of these forces act to drive objects from their initial non-resonant positions into resonant configurations where they can become permanently trapped.

Interestingly, the physics of resonance trapping is largely independent of the details of the resonant force, whether it is the gravity of an orbiting satellite, the gravity of a non-axisymmetric planet, or the Lorentz force from a spinning magnetic field (Hamilton 1994). Thus, the mathematical apparatus developed for satellite resonances may be applied to their more exotic non-gravitational counterparts and, conversely, the study of non-gravitational resonances can enhance our understanding of gravitational phenomena.

Most of these similarities are enforced by very simple physics, primarily orbital symmetries and the Jacobi Constant. In this talk, I will use these concepts to elucidate the main features of resonant dynamics and answer the following questions: Why do different resonances behave similarly? When can resonant trapping occur? Do equilibrium configurations exist and, if so, under what conditions are they stable?

Lunch

Session 3. COLLISIONS — H. Levison, Chair

INVITED TALK - Asteroid hazard: algorithms for computation of actual cases

A. Milani (Department of Mathematics, University of Pisa, Italy), G.B. Valsecchi (Institute for Space Astrophysics, CNR, Roma Italy), S.R. Chesley (JPL, NASA/Caltech, Pasadena, CA)

We report on the recent breakthrough in the methods to detect computationally the possibility of an asteroid impact, even at low probability levels. The problem is to propagate the uncertainty cloud of the asteroid initial conditions for a time span of decades, to detect intersections with the orbit of the Earth, and to estimate the corresponding probability. The linear approximation algorithm is often enough for the next encounter, but the most dangerous close approach result from resonant returns, in which a gravity assist from the Earth inserts in a mean motion resonance, and non resonant returns, a similar mechanism recently identified. The cascade of successive returns to close approach generates a complicate, fractal-like structure which can so far be explored only numerically. All the algorithms successfully used are based on the selection of a finite number of Virtual Asteroids sampling the uncertainty cloud; rather than the random sampling of the Montecarlo methods, we show the advantages of assembling the Virtual Asteroids in a string, along which the existence of Virtual Impactors may be proven by geometric arguments. The full understanding of these violently chaotic dynamical phenomena, by means of explicit, analytic theories, is in progress, but numerical methods are already in use for daily monitoring.

Research sponsored by Univ. of Pisa, CNR, NSF/NATO, Spaceguard Foundation

An Automatic Earth-Asteroid Collision Monitoring System

S.R. Chesley (JPL), A. Milani (Dept. Mathematics, Univ. Pisa)

A fully automatic system to monitor the known near-Earth asteroid populaton for potential collisions with Earth has been operating at the University of Pisa since November 1999. The system, known as CLOMON, maintains a prioritized queue of objects to be processed, where the prioritization in the queue is based on a score that attempts to quantify the likelihood of finding a collision solution. This score is based on the nominal MOID, the positional uncertainty at some far future epoch, and the amount that the uncertainty has been reduced by additional observations since the last analysis. The queue is updated and re-sorted daily with the most recently published observational and discovery information. When an object reaches the head of the queue CLOMON searches for orbits which are both compatible with the available observations and lead to collision with Earth. The system automatically sends an email notification in the event that a threatening encounter is discovered.

CLOMON identified its first potential impactor on February 7, 2000 when the asteroid 2000 BF_{19} was found to have a potential Earth collision in August 2022 with a probability of approximately 10^{-6}. This case will be summarized, and the current protocol for announcing potential collision solutions will be described.

Estimating Impact Probability Using Monte Carlo Techniques

P.W. Chodas (JPL/Caltech)

The probability that an asteroid or comet will collide with the Earth during a future close passage depends on its orbit uncertainties during that encounter. These uncertainties in turn depend on the duration over which the object has been observed, and the time interval from the last observation to the encounter. Linear techniques for analyzing encounter uncertainties are elegant and fast, and can be used to obtain a quick estimate of impact probability. But if orbit uncertainties during the encounter are large, due to a short data arc, or a long prediction interval, or intervening close approaches, the linear method breaks down. Monte Carlo techniques can be used to overcome these obstacles, enabling analysis of encounters farther in the future than would otherwise be possible. Although these methods require considerably more computation than linear techniques, the computational load is not prohibitive. Our Monte Carlo method begins by populating the uncertainty region in epoch orbital element space with thousands of random points. Each of these is numerically integrated to the encounter of interest, and the target-plane asymptote intercept coordinates are computed. A straight-forward estimate of collision probability is just the ratio of impacting points to the total population. If the points are too sparse, however, a collision probability can be obtained by splitting the points into linearly related streams, deriving a local point density both along the line of variation and perpendicular to it, and integrating this 2D density over the Earth disk. Use of this technique for estimating impact probabilities of asteroids 1999 AN10, 1998 OX4, and 2000 BF19 will be discussed.

The Population of Near-Earth Asteroids

A.W. Harris (Jet Propulsion Laboratory, Caltech)

For purposes of defining a population vs. size, we define a Near-Earth asteroid as one with a perihelion less than 1.3 AU, and we measure size in terms of absolute magnitude H, rather than actual size. Earlier estimates of the population with H ¡ 18.0 (generally considered to correspond to diameter ¿ 1 km) range from as many as 2000 to as few as 750. I have estimated the population in two ways: (1) by extrapolating a model fit over the range where surveys are complete already (H ¡ 14.5) down to H = 18.0; and (2) by dividing the numbers of already discovered asteroids by the ratio of the number of new discoveries to total detections (new plus re-detections) in the last year. Method (1) yields a population estimate of about 1500 brighter (larger) than H = 18.0, and method (2) yields about 1000. The uncertainty in either method is about equal to the separation between the values.

This research was supported by NASA under contract to JPL.

The Statistics of Large Impacts on the Terrestrial Planets

L. Dones (SWRI), K.J. Zahnle (NASA Ames), W.F. Bottke, Jr. (Cornell), H.F. Levison (SWRI)

The cumulative mass distribution of small bodies in the Solar System is often taken to be a power law, $N(>m) \propto m^{-\gamma}$, with $\gamma < 1$. A theoretical strength-independent collisional cascade has $\gamma \sim \frac{5}{6}$ (J. S. Dohnanyi 1969, *J. Geophys. Res.* **74**, 2531; D. R. Williams and G. W. Wetherill 1994, *Icarus* **107**, 117; H. Tanaka *et al.* 1996, *Icarus* **123**, 450; D. D. Durda *et al.* 1998, *Icarus* **135**, 431). Present-day impacts on the Earth and Moon are generally thought to be dominated by asteroids. For Near-Earth Asteroids (NEAs) with diameters $d > 0.2$ km, the Spacewatch and NEAT surveys found $\gamma = 0.66$ and 0.58, respectively (D. L. Rabinowitz 1993, *Ap. J.* **407**, 412; D. L. Rabinowitz *et al.* 2000, *Nature* **403**, 165). The distribution apparently steepens to $\gamma \sim 0.8$–0.9 for NEAs with $d > 5$ km (W. F. Bottke *et al.* 2000, *Science*, in press). Finally, the application of impact scaling relations to crater counts on the Moon, Mars, and Venus yields values of γ ranging from 0.5 to 0.9 (K. J. Zahnle and N. H. Sleep 1997, in *Comets and the Origin and Evolution of Life*).

Impactor distributions with $\gamma < 1$ are top-heavy; much of the total mass is likely to be delivered by one or a few bodies, and the characteristic total mass that has struck a planet after N impacts scales as $N^{1/\gamma}$ (S. Tremaine and L. Dones 1993, *Icarus* **106**, 335; A. D. Anbar *et al.* 2000, *JGR Planets*, submitted). As part of a study of one model for the lunar Late Heavy Bombardment (H. F. Levison *et al.* 2000, *Icarus*, in preparation), we are investigating the statistical properties of the largest impactors on the Moon and Earth. Here we ask: Based upon the Moon's post-mare cratering record, how big was the largest body to strike the Earth in the last 3 billion years? Our preliminary results suggest that at least one Imbrium-scale impact ($\sim 2 \times 10^{33}$ ergs, some 100 times more energetic than the K-T impact 65 Myr ago) is likely if $\gamma < 0.9$. Assuming an asteroidal impactor, the mass of the putative impactor is $\sim 10^{21}$ g, which is at least 10 times the mass of the largest present-day NEA, 1036 Ganymed (P. Michel *et al.* 1999, *Astron. Astrophys.* **347**, 711). We will discuss the sensitivity of these results to our assumptions about the transport of asteroids from the main belt to 1 AU, and will touch on the implications for the history of life on Earth. This work was supported by the NASA Origins and Exobiology programs.

Giant Impacts and the Distribution of Planetary Obliquities

J.J. Lissauer (NASA Ames Research Center), E.J. Rivera (SUNY Stony Brook), M.J. Duncan (Queen's Univ.), H.F. Levison (Southwest Research Institute)

We have conducted a set of 200 numerical experiments to test the hypothesis that a giant impact leading to the formation of Earth's Moon could have occurred tens of millions of years after most of the small debris in the inner Solar System had been incorporated into terrestrial planets or been removed from the region. More than half of these simulations ended with a giant impact between two of the five terrestrial planets that were initially present. Neglecting any rotational angular momentum prior to the collision, the merged planet typically has a rotation period of less than five hours. The mean planetary obliquity is 91.7 degrees, and the median is 87.9 degrees; thus, there is no statistically significant difference between the number of bodies with prograde rotation and the number with retrograde rotation. There is a paucity of planets with obliquity close to 90 degrees, but the total number of impacts was too small for this result to be of much significance.

Several encounters leading to collisions are dominated by 3-body effects, with the velocity at impact being slightly less than the free-space escape velocity of the two bodies; the obliquity distribution produced by these impacts appears to be random.

This research was supported in part by NASA's OSSRP under grant NAG 5-4640

Soft Drink Break - Poster Session

On the dynamic stability of Saturn's F ring

F. Poulet (NASA ARC/NRC), S. Jancart (University of Namur)

We explore the dynamics of Saturn's F ring by following the orbital histories of circumplanetary particles between the orbits of Prometheus and Pandora. Our goal is to find structures that could be related to the F ring. Using a 3-D mapping integrator developped by Sicardy and Foryta (1996), we follow the behavior of several thousand test particles distributed unformly between 140,000 and 140,400 km in order to acquire a general picture of the dynamics of this zone. The model includes the gravitational effects of Saturn (up to J_4) and the two shepherd satellites.

The numerical simulations show chaotic behaviors of the particles resulting in a close encounter with one or the other of the satellites, which deplete the zone between the satellites. The timescale over which particles are removed by the satellites is of order a ten thousand years. After a hundred thousand years, some particles exist but they are not related to the actual four strands of the F ring. As suggested by Cuzzi and Burns (1988), these simulations indicate that this ring may be a transient event occuring at the edge of the Roche limit. However, taking into account dissipation (collisions, viscosity) might help to explain the longevity and the location of this ring.

This work was performed while the author held a National Research Council - NASA ARC Research Associateship.

Minimal Orbital Intersection Distance: computation, uncertainty, and secular evolution

A. Milani, G.F. Gronchi and C. Bonanno (University of Pisa, Italy)

A method to compute the secular evolution of Near Earth objects is given; this is based on a generalized averaging principle and on a singularity extraction method which employs an approximation due to Wetherill in Opik's reference frame. This theory can be used to compute proper elements and proper frequencies for planet crossing objects. The same approximation leads to an analytical estimate for the minimum distance between two elliptical orbits (MOID) which allows to compute the range of possible MOIDs in accordance with the uncertainty in observations. This is done taking into account all the local minima of the distance between the two orbits using an algebraic method for the computation of all the stationary points of the problem.

Session 4.
RINGS L. Dones, Chair

Modeling the Azimuthal Brightness Asymmetry in Saturn's Rings

H. Salo, R. Karjalainen (U. of Oulu), R.G. French (Wellesley C.)

Dynamical N-body simulations suggest the formation of transient, recurrent particle chains in the outer portions of Saturn's rings, due to local gravitational instabilities. The scale of these "wakes" is in the range of few tens to few hundreds meters. Due to differential rotation these formations trail on the average by about 20^o with respect to the tangential direction. The amplitude of the wakes depends, besides the ring surface density and the planetocentric distance, on the local velocity dispersion determined by the elastic properties and the size distribution of the particles. Such wakes seem to offer a natural qualitative explanation for the observed azimuthal brightness variation in Saturn's A-ring (Dones *et al.* 1993, *Icarus* **105**, 84): the bi-symmetric brightness minima can be intepreted to correspond to the longitudes where the wakes are seen along their long-axis (about 20^o before the ansae). To study more quantitatively the photometric implications of such wakes, Monte Carlo simulations including multiple scattering have been performed. These simulations yield the scattered intensity from the particle field as a function of the illumination and viewing directions, and thus a model for the ring brightness along the longitude. These photometric simulation fully confirm the expectation of the locations of the brightness minima.

We have started exploring models where the different parameters affecting the dynamical amplitude of the wakes are varied, with the goal of eventually matching the observed amplitude of brightness variations as a function of Saturnocentric distance. Also, photometric simulations are performed for different observing geometries (the Sun-observer phase angle and the ring tilt angle). So far, simulations indicate a strong increase in the brightness amplitude with the surface density and distance. Also, the elasticity of particles can not greatly exceed that implied by Bridges *et al.* (1984, *Nature* **309**, 333) model. Simulations with power-law size distribution imply a reduction in amplitude by about one half as compared to models with single-sized particles, in qualitative agreement with the recent HST (French *et al.*, this meeting) and radar (Nicholson *et al.*, this meeting) observations.

HST Observations of the Azimuthal Brightness Asymmetry in Saturn's Rings

R.G. French (Wellesley C.), L. Dones (SWRI), H. Salo (U. of Oulu)

Azimuthal brightness variations in Saturn's rings were first noted by Camichel (1958, *Ann. d'Astroph.* **21**, 231), and Thompson *et al.* (1981, *Icarus* **46**, 187) showed that the amplitude of the variations varies with tilt angle, reaching ±20% in the brighter parts of the A ring. The A ring's asymmetry is even more pronounced in Voyager images of the unlit face of the rings (Franklin *et al.* 1987, *Icarus* **69**, 280). In low-phase, lit-face images, Dones *et al.* 1993 (*Icarus* **105**, 184) found that the asymmetry's amplitude shows a narrow peak in the mid-A ring. The most promising explanation for the asymmetry invokes the spontaneous formation of transient gravitational "wakes" (*e.g.,* Colombo *et al.* 1976, *Nature* **264**, 344; Salo *et al.* 2000, this meeting), which can form more easily further from Saturn due to the weaker tidal forces there. Taking advantage of the remarkable resolution and photometric accuracy of the Hubble Space Telescope's WFPC2, we have accurately measured this asymmetry as the rings have changed from their nearly edge-on aspect to their current more open configuration. Our observations span the full range of phase angles accessible from the Earth ($\alpha < 6°$), with densest sampling near opposition, at wavelengths from 255 nm to nearly 1 μm, including the standard UBVRI filter set. The amplitude, phase, and shape of the brightness asymmetry vary substantially with ring orbital radius, sub-solar longitude, solar phase angle, and ring opening angle as seen from the Earth (B) and the Sun (B'). The asymmetry varies only slightly with wavelength, due perhaps to the relative unimportance of multiple scattering over a range of ring albedos. We compare the measured amplitude, location of minimum brightness, and detailed shape of the azimuthal variations with profiles predicted using N-body simulations of gravitational instabilities (Salo *et al.* 2000, this meeting). The agreement is remarkably good, both confirming the underlying physical explanation for the asymmetry and providing strong constraints on ring particle properties. This work was supported in part by NASA Grant GO-06806.01-95A.

The first radar images of Saturn's rings.

P.D. Nicholson, D.B. Campbell (Cornell University), R.G. French (Wellesley College), G.J. Black (NRAO), M. Nolan, J-L. Margot (NAIC)

In October 1999 we obtained the first radar images of Saturn's rings, using the recently-upgraded Arecibo telescope operating at a wavelength of 12.6 cm. The opening angle of the rings was 19.9°, and dual-circular polarization data were collected over a period of 5 days. The resulting delay-Doppler maps have a range resolution of 100 msec and a frequency resolution of 2 kHz, corresponding to a spatial resolution cell of 15000×2000 km. Previous radar observations (*e.g.,* Ostro *et al.* [1982] *Icarus* **49**, 367) demonstrated the rings' high cross section and depolarization ratio, but did not yield 2-dimensional images. The most striking feature of the new maps is a very pronounced azimuthal asymmetry in the brightness of the A Ring, reminiscent of that seen in some ground-based and Voyager images, and more recently documented in HST images (see French *et al.*, this meeting). In both circular polarizations, the rings are brighter on the far quadrant on the receding (western) ansa and on the near quadrant of the approaching (eastern) ansa. The asymmetry averages 25%, but appears to be greater on the eastern ansa. The azimuthal asymmetry is generally ascribed to small-scale trailing wakes generated by local gravitational instabilities in the rings, and as such may be expected to be more pronounced among the meter-sized particles which dominate the radar cross-section than for the cm-sized and smaller particles which contribute significantly to the rings' visible reflectivity. We have attempted to isolate the source of asymmetry by generating synthetic delay-Doppler images of the individual ring components and subtracting these piecewise from the Arecibo images. These models show that the azimuthal asymmetry is indeed concentrated in the A Ring, where it is at least twice as strong as that seen in nearly simultaneous HST images at 439 nm. The models also suggest a smaller asymmetry in the B Ring, with the same phase as that in the A Ring. Also noteworthy is the apparent absence of any detectable echo from the C Ring. At the 3σ level, we can set an upper limit of 0.06 on the ratio of its cross-section to that of the B Ring, which may be compared to a reflectivity ratio of ~ 0.2 at optical wavelengths and low phase angles.

Dynamics of Clumps and Strands in Saturn's F Ring

M.R. Showalter (Stanford)

Continuing analysis of the Voyager images has shed more light on the kinematics of clumps in Saturn's narrow F Ring. Principal properties are as follows. (1) At any given time, the ring holds 2–3 extremely bright clumps (each several times brighter than the local average for the ring) and perhaps 20–40 identifiable smaller clumps. In practice, the closer one looks at the rings, the finer detail one finds. (2) No major clumps persist for the nine months between the Voyager encounters, but most survive for the periods of up to 7 weeks they can be detected during a single encounter. (3) Clumps travel at distinct mean motions, indicating semi-major axes a generally in the range $140,225 \pm 15$ km. These correspond to the brightest "γ" strand in the Voyager images (Murray et al., Icarus 129, 304–316, 1997). (4) However, additional clumps are observed to travel at faster speeds, corresponding to $a = 140,150$–$140,210$ km. These may correspond to the "β" strand but are more widely distributed. (5) In the Voyager 2 images, the single most prominent clump seems to eject smaller clumps behind it on time scales of ~ 2 weeks. However, nothing analogous is observed in Voyager 1 data. (6) A few close-up images of the fainter strands show radial variations that suggest the presence of high-order radial modes. (7) The brightest clumps are often seen to be radially displaced (either inward or outward) from the surrounding strands. This would suggest that they differ in orbital eccentricity from the surrounding material. (8) Most sections of the ring show a distinct 3.2° periodicity in clump spacing, as expected from the gravitational perturbations by Prometheus. Dynamical models for some of these peculiar properties will be discussed, but many remain unexplained.

The viscosity in an optically thick planetary ring

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

We have investigated the viscosity (angular momentum transfer rate) in an optically thick planetary ring through local N-body simulations including both gravitational interactions and inelastic collisions between ring particles. As Salo(1995) and Daisaka and Ida (1999) showed, in an optically thick planetary ring, wake structure with 100 meter size is formed by self-gravity and collisional damping. The wake structure is non-axisymmetric and it significantly enhances angular momentum transfer rate (viscosity) in the ring.

We separately calculate the gravitational viscosity due to torque caused by the wake structure, the translational(local) viscosity, and the collisional viscosity from the results of our N-body simulations.

The viscosity is evaluated analytically and numerically in the ring system without the self-gravity, where wake structure does not develop (e.g., Goldreich & Tremaine 1978, Araki & Tremaine 1986, Wisdom & Tremaine 1988). The results of our N-body simulations are as follows:

1. The viscosity is consistent with that in the previous studies when optical depth (τ) is smaller than unity and wake structure is weak.

2. If τ exceeds unity, the gravitational viscosity and the local viscosity due to collective motion of the particles caused by the wake structure overwhelm the collisional viscosity and the local viscosity due to random motion. The total viscosity is considerably larger than that in the non-self-gravity case. For Saturnian B-ring parameter, the enhancement factor is as large as 10.

3. In the case with $\tau > 1$, the gravitational viscosity is always nearly equal to the local viscosity due to the collective motion, and the total viscosity is given by $\simeq 10G^2\Sigma^2/\Omega^3$ where Σ is the surface density of the ring and Ω is Keplerian frequency.

More global ring dynamics should be reconsidered by the viscosity we found.

New Dynamical Mass Estimate for the Uranian Alpha Ring

I. Mosqueira (NASA Ames Research Center, and Lick Observatory, UCSC), P.R. Estrada (Department of Astronomy, Cornell University)

The leading model to account for the apse-alignment of the eccentric Uranian rings relies on the ring self-gravity alone to counter differential precession (in the case of $m = 1$ modes), and differential rotation (for all other m modes). In this model, the role of the ring viscosity is simply to produce a small apsidal shift between the inner and the outer ring streamlines. While ring observations have qualitatively confirmed several of its predictions, such as increasing eccentricity with streamline semi-major axis and small, negative apsidal shifts, the self-gravity model yields ring mass estimates based on the observed ring state severely at odds with observational mass estimates based on radio occultation constraints of particle sizes.

Here we introduce a fluid pressure correction applicable to a highly collisional, compresible fluid with low particle velocity dispersion and finite particle sizes. In particular, we model a ring state where the particles are locked in their relative positions and jammed against their neighbors, and the velocity dispersion is so low that collisions are nearly elastic. We then find an equilibrium solution such that the ring self-gravity maintains apse-alignment not only against differential precession but the fluid pressure as well. We apply this model to the Uranian alpha ring, and show that, compared to the previous self-gravity model, it can increase the mass estimate for this ring by an order of magnitude.

Effects of Particle Size on Wakes at the Encke Gap

M.C. Lewis, G.R. Stewart (Laboratory for Atmospheric and Space Physics)

We will look at the effects caused by particle size distributions on the behavior of the wakes formed at the Encke Gap. The results of simulations using power-law size distributions and bi-modal distributions will be compared to simulations using a single particle size and, where possible, observations. The simulations are performed with a code that uses guiding center coordinates to evolve up to 1,000,000 smooth, inelastic particles and ignores the self gravity of the particles. Included in the results will be damping rates for the wakes as well as pressure tensor analysis. We will also test the idea put forward by Shu and Stewart (1985) that the dynamics of a power-law distribution with slope of -3 can be modeled accurately by a single particle size. Funding provided by the Cassini Project, contract 961196 and by NASA grant NAG5-4163.

A scenario of Saturn's ring formation

F. Poulet (NASA Ames Research Center/NRC)

The problem of Saturn's massive and youthful rings is well-know: Saturn's ring system (especially its A ring) could not survive for longer 100 millions years. This implies that the rings seem to have resulted from a very unlikely event, perhaps the destruction of a moon impact cometary or tidal disruption of a large comet passing within Saturn's Roche radius.

I present another scenario of formation and evolution rings in the light of the dynamics of Prometheus-Pandora, Saturn's inner satellite pair. These moons have resonances with the rings, pull angular momentum out of the rings and therefore evolve outward. This effect is particulary rapid because Prometheus (larger and closer to the rings) should overtake Pandora in less 100 million years. The most likely outcome of the close encounter between these two satellites is a catastrophic disruption. This indicates that collisions between inner ring moons take place, and thus could have replenished the rings.

As a result, the formation and evolution of Saturn's rings could be as follows. Sometime in the past (more than 10^8 years ago), a large disruption or a comet capture occurred, which created small satellites and ring particles. These pieces interacted between themselves and spread. The largest moons were pushed away from the rings at different rates until a close approach between two moons, most likely a collision, occurred. Either the satellites are disrupted and form debris, which could take the form of rings plus several large pieces (similar to the case of the orbital evolution of Prometheus and Pandora), or they accreted to form a new satellite. New satellites could reaccrete from a debris disk. In summary, this scenario involves recycling material, with repeated cycles from moons to rings and back to moons again. Such an evolution created the state that we see now.

This work was performed while the author held a National Research Council- NASA ARC Research Associateship.

Session 5.
GALACTIC DYNAMICS D. Merritt , Chair

BROUWER PRIZE LECTURE
Individual and Statistical Aspects of Star Motions[1]

V.A. Antonov (Pulkovo Observatory, St. Petersburg)

The Orbital Structure of Eccentric Nuclear Disks

T.S. Statler, R.M. Salow (Ohio Univ.)

HST observations suggest that eccentric disks may be common in the nuclei of galaxies containing supermassive black holes. The nearest example, M31, shows a double brightness peak and an asymmetric rotation curve, both of which are consistent with a simple stellar disk model introduced by Tremaine (1995). In this model the off-center peak is produced by stars lingering at the apocenters of their orbits about the central black hole. Such a disk may be a long-lived structure, if the gravitational effects of the disk itself (and the surrounding bulge) can conspire with the orbital dynamics to make the entire disk precess uniformly. We examine the structure of orbits in nearly Keplerian potentials perturbed by a slowly precessing eccentric disk, and characterize the major periodic families. Disks with fairly low velocity dispersion will be dominated by stars on quasiperiodic orbits whose periodic parents are nearly elliptical orbits aligned with the disk. We show, however, that it is not possible to find a sequence of such orbits with slowly varying eccentricities, as in the Tremaine model. Instead, the sequence of closed orbits through the densest part of the disk must follow a steep eccentricity gradient, which reverses the arrangement of pericenter and apocenter with respect to the central mass. Stars making up the inner part of the density concentration will be at apocenter, while stars making up the outer part will be at pericenter. This effect may produce observable features in the kinematic profiles at HST resolution.

This work is supported by NSF CAREER grant AST 97-03036.

Reference: Tremaine, S. 1995, AJ, 110, 628

Self-Consistent Models of Eccentric Nuclear Disks

R.M. Salow, T.S. Statler (Ohio Univ.)

We have constructed approximate self-consistent models of eccentric stellar disks. Our models include a self-gravitating disk with finite velocity dispersion which precesses about a central black hole. These models are constructed via a self-consistent iteration scheme in which a disk

[1] paper read by D. Merritt

is populated by a sequence of finite-dispersion orbits whose parents are numerically integrated closed periodic orbits. Once an initial model is assumed, a set of uniformly precessing closed periodic orbits is found in the potential of the disk/black hole system, which is then used to construct a new disk using an approximate phase space distribution function written in terms of the integrals of motion in the two-dimensional Kepler problem. This cycle continues until an equilibrium configuration is found. Results show that there exist various combinations of disk precession speed, disk mass, and orbital dispersion for which converged equilibrium disks can be found. Analysis of these models shows that they have rotation and dispersion profiles that resemble those of M31, as observed by the HST Faint Object Camera. We will discuss these similarities, paying particular attention to the asymmetries and fine structure in the profiles. Also, we will consider how the velocity profiles change with changing parameter values, and how the information contained in them can possibly be used to constrain the disk dynamics, disk mass, and black hole mass for systems such as M31 and NGC4486B.

Tidal Perturbation and Markarian Activity in Disk Galaxy Pairs

G. Byrd (University of Alabama, Tuscaloosa), M. Valtonen (Tuorla Observatory, Turku University)

Ideas of nuclear activity mechanisms in disk galaxies range from internal bars to external tidal perturbation by passing companions. The Byrd et al. (1986, 1987) simulation survey determined the tidal perturbation to induce activity in the nucleus. We compare these simulations and theory to Markarian activity in Karachentsev's (1983) disk galaxy pairs. For double galaxies, we derive for the tidal hypothesis that: (1) There should be an excess of pairs where both are active over pairs with one active (2) Nuclear activity should be preferentially excluded from pairs which are unequal and favorably distributed to pairs where members are equal. (3) Pairs where one or both members are active should have a smaller velocity difference times separation than if both are normal. (4) The average size of pair members to create activity can be smaller if the pair members are equal in size than if they are unequal. These tidal traits are seen in Karachentsev Markarian pairs where both are S type. Observational surveys have raised doubt as to the tidal explanation of Seyfert type activity in galaxies with some suggesting a weak or nonexistent correlation between tidal perturbation and activity compared to a normal sample. The simulations show a several hundred million year delay in the appearance of activity after perturbation and a similar length duration which can explain the these null results.

This work was supported by the Academy of Finland. GB expresses gratitude for the hospitality of Tuorla Observatory in Finland during a winter/spring 1999 visit.

Coffee Break - Poster Session

The Galaxy Interaction and Merger Rates: A Science Scenario for a National Virtual Observatory (NVO)

K.D. Borne (Raytheon ITSS, GSFC), C.Y. Cheung (NASA, GSFC)

We have analyzed the multiplicity function of the galaxies in the recently published UZC (Updated Zwicky Catalog). We have determined the frequency of pairs, triples, and other small-N

groupings. Of the 19,000+ galaxies in the catalog, there are 1600 multiple systems with known redshifts $z<0.08$. We use this sample to estimate the Galaxy Interaction Rate (8%) and Merger Rate ($\sim$0.4 major mergers per galaxy per Hubble time) in the local universe and to determine properties of the multiple galaxies. Archived data and astronomical catalog information available on-line from NASA's ADC (Astronomical Data Center) and from NED (NASA Extragalactic Database) are used to provide a firm physical basis for the interaction interpretation of these multiple galaxy systems. This project represents a typical research scenario that will be enabled through the implementation of a National Virtual Observatory (NVO). The envisioned NVO would be accessible from any astronomer's desktop. The data and metadata holdings of such on-line archives as ADC and NED will provide valuable information and database content for the NVO. The NVO will enable more complicated multi-spectral archival research investigations and cross-survey correlations from the impending multi-terabyte data avalanche coming from existing and future digital sky surveys (e.g., Sloan, 2MASS, DPOSS, NVSS, GALEX, FAME). (This research was supported under NASA contract NAS5-98156.)

NGC 4314 - a Galaxy Dynamicist's Playground

G.F. Benedict (McDonald Obs., UTexas), D.A. Howell (Dept. Astronomy, UTexas), I. Jorgensen (Gemini Telescope Project), B.J. Smith (Physics Dept., E. Tenn. State U.), J.D.P. Kenney (Dept. Astronomy, Yale U.)

Every morphological feature of NGC 4314 (see http://oposite.stsci.edu/pubinfo/pr/1998/21/) is a consequence of stellar or gas dynamics. Past studies have presented photometric evidence for a number of Lindblad Resonances (Benedict et al. 1992. AJ, 103, 757) and have established the dynamics of molecular gas associated with a 20 arcsec diameter nuclear ring (Benedict, Smith, & Kenney 1996, AJ, 112, 1318). Present day star formation is found nowhere but in this ring.

UBVIH-alpha photometry with Hubble Space Telescope WFPC-2 has provided a means to estimate the ages of star clusters associated with the nuclear ring and for two fainter blue arcs just exterior to the ring. Our chronology suggests that the present epoch of star formation has lasted $\sim$20My and that the arcs derive from a similar episode that occurred $\sim$150My ago.

We still lack a satisfactory explanation for the shape and placement of the blue arcs. Future studies (dynamical modeling and integral field spectroscopy of H-alpha emission) may allow us to distinguish between a shrinking ring and spiral pattern driven by a nuclear bar.

Benedict thanks the HST Astrometry Science Team (W. H. Jefferys, P.I., O. G. Franz, W. van Altena, R. Duncombe, P. J. Shelus, L. W. Fredrick, and P. D. Hemenway) for their support and encouragement.

This research was supported by NASA Grant NAG5-1603 from Goddard Spaceflight Center.

Observational Model for the Space Interferometry Mission

S.G. Turyshev, M.H. Milman (Jet Propulsion Laboratory)

The Space Interferometry Mission (SIM) is a space-based long-baseline optical interferometer for precision astrometry. One of the primary objectives of the SIM instrument is to accurately determine the directions to a grid of stars, together with their proper motions and parallax, improving a priori knowledge by nearly three orders of magnitude. The basic astrometric observable of the instrument is the pathlength delay, a measurement made by a combination of internal metrology measurements that determine the distance the starlight travels through the two arms of the interferometer and a measurement of the white light stellar fringe to find the point of equal pathlength. Because this operation requires a non–negligible integration time to accurately measure the stellar fringe position, the interferometer baseline vector is not stationary over this time period, as its absolute length and orientation are time–varying. This conflicts with the consistency condition necessary for extracting the astrometric parameters which requires a stationary baseline vector. This paper addresses how the time-varying baseline is "regularized" so that it may act as a single baseline vector for multiple stars.

Oral Presentations:

The Ultra-Luminous IR Galaxy Interaction Rate

K.D. Borne (Raytheon ITSS, GSFC), R.A. Lucas (STScI), L. Colina (Instituto de Fisica de Cantabria, SPAIN), H. Bushouse (STScI)

We have examined the morphological and local environmental properties of a large sample of ultraluminous IR galaxies (ULIRGs) with the Hubble Space Telescope (HST), giving special attention to those that were previously classified as non-interacting. We find that nearly every such case does in fact show signs of tidal interaction (asymmetric distortions) or evidence for nearby companions, or both, under the scrutiny of the high-angular resolution capability of HST. The interaction frequency of ULIRGs, which has been debated in the literature to be somewhere in the range 50–100%, is actually very close to 100%. Most ULIRGs appear to be undergoing a super starburst that has been generated in a collision/merger event. Members of the sample whose IR luminosities appear to be powered predominantly by a QSO, and thus not dominated by an interaction-induced super starburst, are also found to have faint nearby companions. Most of these companions are very close to the QSO and thus require the subarcsecond resolution of HST for PSF-separation, detection, and verification. (This research was supported under NASA grant number GO-06346.01-95A from the Space Telescope Science Institute, which is operated by AURA, Inc., under NASA contract NAS5-26555.)

Star Formation in One and Two-Fold Resonance Ring Galaxies

T. Freeman (Bevill State, AL USA), G. Byrd, D. Ousley, D. Domingue (University of Alabama, Tuscaloosa, AL USA)

Resonance rings of star formation are a common phenomenon of early type barred spiral galaxies. Rings form by gas cloud gravitational coelesence near resonances with a turning perturbation. The resulting bright stars trace out the rings. We show how to use the Byrd et al. (1998) analytic formulation to model two-fold resonance rings with an example, NGC 3081. We obtain bar strength, orientation, and pattern speed reproducing the observed shapes and radial velocities. We show that an additional type, a one-fold resonance ring, can be produced by lop-sided perturbations. We identify shape, star formation, and velocity signatures of one-fold versus two-fold rings. As an example, we model the one-fold ring of NGC 4622. We study star formation in rings in more detail. Age of associations can be predicted as a function of angle around the ring. Correlating with observed colors or other age indicators permits empirical calibration of the indicator to study star formation and the ages of stellar complexes in other galaxies.

Acknowledgements: T. Freeman and G. Byrd were supported by NSF grant 9802918. D. Ousley was supported by a Univerisyt of Alabama Mc Wane Undergraduate Research Fellowship. We thank R. But and G. Purcell for observational data on NGC 3081.

Fission: A Mechanism for Forming Binary Stars

J.E. Tohline, J.E. Cazes (LSU)

We demonstrate that it is possible for short period binary star systems to form from a single, rapidly rotating, equilibrium protostellar gas cloud via a natural fission process. This is analogous to the process by which rapidly spinning drops of fluid have been observed to break in two during drop dynamics experiments onboard the space shuttle. In order to demonstrate that fission works in the context of binary star formation, we have used a three-dimensional, computational fluid dynamics technique to, first, construct a rapidly rotating, self-gravitating, equilibrium barlike structure that, by all accounts, appears to be a compressible analog of an incompressible Riemann ellipsoid. Then by slowly cooling this configuration and following its cooling evolution in a fully self-consistent fashion, we have demonstrated that the system contracts along an ellipsoid-dumbbell-binary sequence. Although the hypothesis that binary stars may form via a process of fission has been around for more than 100 years, it has been a difficult hypothesis to test because of the nonlinear dynamical processes involved. This is the first demonstration that fission works in the context of realistic protostellar gas clouds. This work has been supported by the U.S. National Science Foundation through grant AST-9528424, by NASA through grant NAG5-8497, and by a grant of high-performance-computing time through NPACI on machines at the San Diego Supercomputing Center.

INVITED TALK - Microlensing as a Probe of Galactic Dark Matter and Extra-solar Planets

Kim Griest (University of California, San Diego)

We summarize recent result from the MACHO collaboration search for baryonic dark matter in the Milky Way and discuss various possible interpretations. While a halo made entirely of massive compact halo objects (MACHOs) is strongly ruled out by this data, 14-17 microlensing events are seen towards the LMC. These imply either that approximately 20 dark matter in the Milky Way consists of objects of about 0.5 solar masses, or that the Milky Way or LMC stellar distributions are different than current models. If there is time, we will also discuss how microlensing is a powerful new method of searching for extra-solar planets throughout the Galaxy.

Lunch

Session 6.
ASTROMETRY and BINARIES R. Reasenberg , Chair

Astrometry and Bayesian Analysis

William Jefferys (University of Texas at Austin)

Bayesian methods show great promise for astrometry, especially in situations where significant prior information exists or where model selection or model averaging is important. I will discuss examples from work done earlier by H.K. Eichhorn and show how Bayesian ideas can be used to illuminate such problems.

Interferometric Astrometry with Hubble Space Telescope - A Review

G.F. Benedict, B.E. McArthur (McDonald Obs., UTexas), O.G. Franz, L.H. Wasserman (Lowell Obs.), T.J. Henry (Johns-Hopkins), T. Takato (Astronomy Dept., UTexas), I. Strateva (Princeton U.), Astrometry Science Team

We review recent results from fringe tracking (POS) and fringe scanning (TRANS) mode astrometry using Fine Guidance Sensor 3 aboard Hubble Space Telescope. The relatively large field of regard, faint limiting magnitude, and raw resolution of FGS 3 have allowed us to obtain sub-millisecond of arc precision parallaxes for several Cataclysmic Variables (RW Tri & TV Col), a fundamental distance scale calibrator (RR Lyr), a Planetary Nebula central star (NGC 6853), and a hot White Dwarf binary (Feige 24).

We have determined parallaxes, orbital parameters, and masses for low-mass binaries critical to the lower main sequence Mass-Luminosity Relationship (Gl 791.2, Wolf 1062, Gl 623).

The Astrometry Science Team presently consists of W. H. Jefferys, P.I., G. F. Benedict, Deputy P.I., B. McArthur, O.G. Franz, L. H. Wasserman, L. W. Fredrick, W. van Altena, E. Nelan, R. Duncombe, P. J. Shelus, and P. D. Hemenway.

This research had the support of NASA Grants NAS5-1603 (GSFC), and GO-06036.01-94A, GO-07491.01-97A (STScI).

Resolution and Orbit Reconstruction of Spectroscopic Binary Stars with the Palomar Testbed Interferometer

A.F. Boden (IPAC/Caltech), B.F. Lane (Caltech GPS), M.J. Creech-Eakman (JPL/Caltech), D. Queloz (Observatoire de Genève), C.D. Koresko (IPAC/Caltech)

The Palomar Testbed Interferometer (PTI) is a long-baseline near-infrared interferometer located at Palomar Observatory. For the past several years we have had an ongoing program of resolving and reconstructing the visual and physical orbits of spectroscopic binary stars with PTI, with the goal of obtaining precise dynamical mass estimates and other physical parameters. We will present

a number of new visual and physical orbit determinations derived from integrated reductions of PTI visibility and archival and new spectroscopic radial velocity data. The systems for which we will discuss our orbit models are: iota Pegasi (HD 210027), 64 Psc (HD 4676), 12 Boo (HD 123999), 75 Cnc (HD 78418), 47 And (HD 8374), HD 205539, BY Draconis (HDE 234677), and 3 Boo (HD 120064), and 3 Boo (HD 120064). All of these systems are double-lined binary systems (SB2), and integrated astrometric/radial velocity orbit modeling provides precise fundamental parameters (mass, luminosity) and system distance determinations comparable with Hipparcos precisions.

The first US Naval Observatory CCD Astrograph Catalog

N. Zacharias, T.J. Rafferty (USNO), M.I. Zacharias (USRA)

A CD-ROM has been produced with the first U.S. Naval Observatory CCD Astrograph Catalog (UCAC1). This is a high precision, astrometric catalog containing positions and proper motions for 27 million stars. About 80% of the Southern Hemisphere is covered by this preliminary catalog, observed at Cerro Tololo between February 1998 and November 1999. The precision of the catalog is about 20 mas for the 9 to 14th magnitude range and 70 mas at its limiting magnitude of r'=16.

Proper motions were derived using the Tycho-2 including the AC data for the bright stars (r'<=12.5) and the USNO A2.0 for the fainter stars. The precision of the proper motions varies largely (2 to 30 mas/yr) mainly depending on the epoch difference to the first epoch data. External comparisons with Tycho-2 and the Yale Southern Proper Motion (SPM) 2.0 data reveal systematic errors to be only on the 10 mas level.

The UCAC has a density (stars/square degree) exceeding that of the Guide Star Catalog (GSC) with a positional accuracy comparable to Tycho-1. UCAC positions of 10.5 to 12.5 magnitude stars are also much more precise than the Tycho-2 positions.

Robert G. Aitken and His ADS: Double Star Oberver, Cataloguer, Statistician, and Observatory Director

D.E. Osterbrock (UCO/Lick Obs., UCSC)

Robert G. Aitken was a dynamical astronomer of the old school, a long-time visual double star observer. He was born in 1864 in Jackson, California, a small town in the Gold Country midway between Yosemite and Sacramento. His education at Williams College under Truman Safford; his early teaching career at Livermore College and the University of the Pacific; his simultaneous graduate reading course in mathematics; and his becoming a professional astronomer under the tutelage of Edward S. Holden and Edward E. Barnard at Lick Observatory will be described.

Aitken made a systematic survey of the entire sky north of -30 degrees for double stars, joined by William J. Hussey for a time. It produced important new information on binary and multiple stars and their orbits. His book *The Binary Stars* and his *New General Catalogue of Double Stars (ADS)* were his monuments.

Aitken was associate director of Lick Observatory from 1923 until 1930, while W. W. Campbell was simultaneously director and president of the University of California. Then Aitken was director himself from 1930 until he retired in 1935 and moved to Berkeley, where he continued writing until his death in 1951. Aitken was editor of the *PASP* for 51 years. He hoped that

Gerard P. Kuiper would succeed him as the double star observer at Lick Observatory, but that was not to be.

Aitken at various times held every office in the ASP, and was vice president, then president, of the AAS.

The Suitability of Hipparcos Doubles to Represent the ICRF

T.E. Corbin, S.E. Urban, B.D. Mason (U.S. Naval Observatory)

In Kyoto, the International Astronomical Union passed resolution B2 which made the Hipparcos Catalogue the optical realization of the International Celestial Reference Frame. This resolution does not differentiate between the different types of stars in Hipparcos; the catalogue *in its entirety* currently represents the ICRF at optical wavelengths. The astrometric community now realizes that not all stars in Hipparcos are equivalent. This is especially true in the cases of double stars whose proper motions contain the effects of uncorrected orbital motion. Using the proper motions recently derived at the USNO for the Tycho-2 Catalogue, comparisons are made with the values in Hipparcos. The Tycho-2 data have the advantage of being based on catalog positions spanning almost a century thus averaging out effects of orbital motion in many systems. These comparisons provide the basis to illustrate the characteristics of the double stars and other so-called problem stars. A brief review of the Tycho-2 Catalogue is presented and the suitability of the Hipparcos double and problem stars to represent the ICRF at optical wavelengths is discussed.

Results on the Structure and Mass of the Pleiades from a 2MASS-USNO Proper Motion Search

J.D. Adams (U. of Massachusetts), J.R. Stauffer (CfA), D.G. Monet (USNO Flagstaff), M.F. Skrutskie (U. of Massachusetts), C.A. Beichman (JPL)

Our spatially complete search for low mass members of the Pleiades using 2MASS and USNO proper motions has revealed hundreds of new candidate members down to $\sim 0.1 M_\odot$. This extensive survey has allowed us to determine the mass distribution in the cluster out to the tidal radius. We present a precise estimate of the stellar mass, including a correction for unresolved binaries, and discuss the radial distribution of low mass stars. We also characterize the highly elliptical projected structure of the halo. These results demonstrate the feasibility of studying the dynamical properties of nearby open star clusters using digital sky surveys.

This presentation makes use of data products from the Two Micron All Sky Survey, which is a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center, funded by the National Aeronautics and Space Administration and the National Science Foundation.

A Search for Stars Passing Close to the Sun, II. Integrated Orbits, Observational Completeness, and Future Missions

P.R. Weissman (Jet Propulsion Laboratory), J. Garcia-Sanchez (University of Barcelona), R.A. Preston (Jet Propulsion Laboratory)

We have continued our analysis of Hipparcos data in order to search for stars which have encountered or will encounter the solar system (Garcia-Sanchez et al. *Astron.J.* **117**, 1042, 1999). Hipparcos parallax and proper motion determinations are combined with ground-based radial velocity measurements to obtain the trajectories of stars relative to the solar system. Our earlier work used rectilinear trajectories. We have now integrated all trajectories in the galactic potential using three different models: a local potential model, a global potential model, and a perturbative potential model. Agreement between the models is generally very good, in particular for encounter times less than ± 1 Myr from the present. Based on the Hipparcos data, we find a frequency of stellar encounters within one parsec of the Sun of 2.3 ± 0.2 per Myr. However, we also find that the Hipparcos data is observationally incomplete. By comparing the Hipparcos data with the stellar luminosity function for stars within 50 pc of the Sun, we find that only one-fifth of the stars were detected by Hipparcos. Correcting for this incompleteness, we obtain a value of 11.7 ± 1.0 Myr^{-1} stellar encounters within one pc of the Sun. We examine the ability of two future missions, FAME and GAIA, to extend the search for past and future stellar encounters with the Sun. This work was performed in part at the Jet Propulsion Laboratory and was supported by NASA.

Astrometry with the Space Interferometry Mission

Stephen C. Unwin (Jet Propulsion Laboratory, California Institute of Technology)

The Space Interferometry Mission (SIM) will be the first space-based optical interferometer designed for precision astrometry. As well as enabling forefront astronomical science, SIM will serve as a technology pathfinder for future missions, in NASA's Origins Program, such as the Terrestrial Planet Finder. SIM expected to yield 4 microarcsecond absolute position measurements of stars down to 20 magnitude. Launch is currently planned for mid-2006, and the mission duration is 5 years. SIM will perform sensitive searches for sub-stellar and planetary companions to nearby stars, and will be sensitive to the astrometric 'wobble' signature to a level of about 1 microarcsecond. With precision global astrometry, SIM will address a important variety of science questions relating to the formation and dynamics of our Galaxy.

This talk will briefly summarize the current status of the SIM project, and will describe the instrument design and operation. For global astrometry, SIM requires a grid of astrometrically stable stars, selected prior to launch. The selection and characterization of candidate stars poses an interesting challenge, which is essentially the inverse of the planet-detection problem. An approach to the astrophysical selection of grid stars will be presented.

Business Meeting

BANQUET TALK
The End of the Universe
Greg Laughlin (NASA Ames)

Session 7.
SPACECRAFT ORBITS R. Jacobsen , Chair

Orbit Determination at Eros: NEAR Spacecraft Dynamics and Initial Results

J.D. Giorgini, J.K. Miller, P.G. Antreasian, B.G. Williams, C.E. Helfrich, W.M. Owen, Jr., T.C. Wang, D.K. Yeomans, E. Carranza, S.R. Chesley (Jet Propulsion Laboratory)

The NEAR spacecraft was maneuvered into a 366x321 km capture trajectory around minor planet (433) Eros on February 14, 2000. Determination and prediction of the spacecraft's motion about the elongated (33x17x13 km) central body provides a richly coupled problem in dynamics due to Eros' ephemeris uncertainties, Eros' weak, non-uniform gravity field, the initially uncertain Eros spin-state, and the influence of solar gravity and radiation pressure on the spacecraft.

A brief review of the mission to date and discussion of the general orbit stability problem is given. This is followed by description of the orbit determination strategy as it relates to a global solution for Eros' gravity field in terms of spherical and elliptical harmonic representations.

Six observational data types have been used simultaneously to solve for these dynamical parameters. They include two-way coherent Doppler, ranging, differenced Doppler, optical surface landmarks, optical center of mass estimates, and the star background.

Initial results, including estimates of the mass parameter, bulk density, pole direction, prime meridian, gravity harmonics and inertia tensor are presented. During the initial orbital phase there is little sensitivity to even low-order gravity harmonics. As the spacecraft moves to lower altitudes, this sensitivity will improve. Plans call for an eventual 35 km circular orbit with specially designed close passes that will come within 1 km of Eros' surface prior to nominal mission end in February, 2001.

Perturbations of a Spacecraft Orbit During an Hyperbolic Flyby

N.J. Rappaport (Jet Propulsion Laboratory), G. Giampieri (Queen Mary and Westfield College), J.D. Anderson (Jet Propulsion Laboratory)

An analytical theory of the motion of a spacecraft during an hyperbolic flyby will be presented. The perturbations considered are those due to the harmonic coefficients C_{20} and C_{22} of the body's gravity field. These harmonic coefficients are the only coefficients of degree two that need to be considered in the case where the gravity harmonic coefficients are refered to the principal axis system of the body. The new theory is a first order perturbation theory with respect to C_{20} and C_{22}. The perturbations of the hyperbolic elements are expressed in function of the unperturbed values of the elements. There are no further approximation with respect to the eccentricity or inclination, i.e., the equations for the variations of the elements do not involve any infinite series. The results of the new theory will be compared with results of numerical integrations and with results predicted by the Anderson and Giampieri theory (1999).

Astrometry-Based Analysis of Cassini's Earth Flyby

R.L. Mansfield (Astronomical Data Service)

This presentation will summarize the results of my analysis of Cassini's Earth flyby of 1999 August 18, based upon two sets of CCD astrometric observations. The first set (11 observations) was taken by G. J. Garradd at Loomberah. The second set (four observations) was taken by R. H. McNaught at Siding Spring. Both sets of observations were obtained from the Project Pluto website (http://www.projectpluto.com/cassini.htm) as posted there by Bill J. Gray.

My analysis applies Herget's method of preliminary orbit determination with the following two modifications.

1. Gauss's hypergeometric X-function is expressed as a quotient of Stumpff's c-functions, rather than as a truncated series. The velocity at the first observation time is solved for explicitly via Gauss's method.

2. Position and velocity at the first observation time are propagated to the intermediate observation times as f and g functions of c-functions.

Further, the analysis uses batch least squares differential correction (DC) to improve the initial estimates of cartesian position and velocity as obtained via Herget's method. The batch DC uses analytical partials based upon W. H. Goodyear's two-body state transition matrix, with Goodyear's s-functions reformulated in terms of Stumpff's c-functions.

The preliminary and improved orbit determination algorithms were implemented in both the heliocentric ecliptic (sun as primary) and geocentric equatorial (Earth as primary) reference frames. Each algorithm was then realized as two complementary Mathcad worksheets, one an "initiator" and the other an "iterator". All four pairs of worksheets were applied to the same set of 15 CCD astrometric observations. I will describe the algorithms as so implemented, their limitations and their capabilities, and the results that I obtained with them.

Coffee Break - Poster Papers

Double Stars in the Tycho-2 Catalogue

B.D. Mason, G.L. Wycoff, S.E. Urban, W.I. Hartkopf, E.R. Holdenried (U.S. Naval Observatory), V.V.Makarov (Copenhagen U)

The Tycho-2 Catalogue (Høg et al. 2000) provides astrometric and photometric information for 2.5 million stars. While within the Tycho-2 Catalogue there is no separate listing of double star parameters, there is a wealth of double star data. For all measured double star systems, each component have their own entry in Tycho-2 (i.e., this corresponds to the Hipparcos "double entry systems") and the classical double star parameters of separation, position angle and magnitude difference can be calculated for these systems. Most double stars within the Tycho-2 Catalogue are identified with a code indicating a double, failed double or photocentric solution. These resulted in 6,251 measures of known double stars and 1,234 new double star systems [designated in the Washington Double Star (WDS) catalog with a "TDS" discovery code]. In an effort to provide additional confirmation for uncertain pairs in the WDS, systems having fewer than three measures were compared in position and magnitude against stars in the Tycho-2 Catalogue. Unexpectedly, 4,726 systems indicated as "single" in the Tycho-2 Catalogue not only matched one component of a WDS pair but had a nearby star which closely approximated the position and magnitude of the other WDS component. Also, these inspections resulted in 2,757 systems with a photocentric solution which, despite not being a resolved measure, tends to support the veracity of those systems. In addition, 5,330 WDS systems were seen as single in Tycho-2. The observational statistics of these various classes of objects are presented as well as catalog statistics for those with single star or photocenter solutions. A quantitative assessment of Tycho-2 double star measures is provided via a comparison of Tycho-2 O-C residuals to known orbits. Finally, some new TDS stars have been verified via speckle interferometry using the 82-inch telescope of McDonald Observatory. These results are presented here also.

The Fifth Catalog of Orbits of Visual Binary Stars — Making the Grade

W.I. Hartkopf, B.D. Mason (U.S. Naval Observatory)

With 17 years having passed since the 1983 Worley & Heintz *Fourth Catalog of Orbits of Visual Binary Stars*, the time is ripe for a new compilation. This *Fifth Catalog* will be maintained and regularly updated on the USNO website; however, due to the long interval since the previous publication, a paper version will be produced this year, as well. We anticipate that the new catalog will be some 30-40% larger than the *Fourth* and will include major revisions to many of the orbits published therein. The *Fifth* will also include ephemerides and figures for all orbits. A sample page of the new catalog is presented; suggestions are welcomed regarding format and further information to be included.

A major component in the production of a new catalog is the determination of grades for each orbit. The W&H grading scheme was based on orbital coverage, number of observations, and their overall quality, and presented on a numerical scale (1=definitive to 5=indeterminate), based on the accumulated experience of the authors and their qualitative assessment of individual observers. While useful for judging the reliability of a given orbit, this scheme was rather subjective, so difficult to duplicate by other cataloguers. A more objective scheme has been explored, which includes weights for each observation (based on grades determined for each observer), weighted rms θ and ρ residuals, total number of observations, phase coverage, and other factors. W&H orbits are evaluated by this scheme, using data available at the time of the *Fourth Catalog*, to determine the correlation between our criteria and the W&H grades. As the final grading scheme has not yet been "written in stone", suggestions are also solicited for other potential grading criteria.

Finally, the problems of grading astrometric orbits, combined solution orbits, and orbits from long-baseline optical interferometry are also discussed.

A Deflection Test of General Relativity Using the FAME Data

R.D. Reasenberg (SAO / CfA)

The deflection of light by the Sun provides one of the classical tests of general relativity. The deflection is closely related to the Shapiro time delay and, in the context of the PPN formalism, each has an overall coefficient of $(1 + \gamma) / 2$. The current published set of strong determinations of the PPN parameter γ are based on Viking radio delay (Reasenberg et al., 1979, ApJL: 1.000 +- 0.002), VLBI data intended for geodesy (Robertson et al., 1991, Nature: 1.0002 +- 0.002), VLBI data for relativity (Lebach et al., 1995, Phys. Rev. Lett: 0.9996 +- 0.0016), and Hipparcos (Froeschle et al., 1997, ESA SP-402: 0.997 +- 0.003). FAME will observe 40 million stars about 1000 times each during a 2.5 year mission, and a 2.5 year extended mission is planned. For V-mag = 9, its nominal measurement accuracy is 1.1 mas along the great circle defined by the

spin direction, which remains about 45 deg from the Sun direction as it precesses around the Sun. Although FAME observations are made as close as 45 deg from the Sun, those have zero sensitivity because they are made in the wrong direction. At 90 deg from the Sun, the deflection seen from Earth is 4.1 mas, which would yield a SNR of 3.7 for FAME, were it not for the "cosine term." The most sensitive measurements are made when the spacecraft has rotated the view port 45 deg from the observations closest to the Sun – Sun-star angle of 60 deg – yielding a single-measurement SNR of 4. A preliminary propagation-of-error analysis shows that a 2.5 year FAME mission has the sensitivity to measure γ with an uncertainty of 3.4 10^{-5}, using all stars from V-mag 5 to 15. However, as was the case for Hipparcos, correlations and systematic errors will result in a larger uncertainty, perhaps 3 to 10 fold larger.

This work has been supported by the Smithsonian Astrophysical Observatory. FAME is a NASA MIDEX mission with the PI at the U.S. Naval Observatory.

Session 8.
RELATIVITY G.F. Benedict , Chair

INVITED TALK - Gravity Probe B

S. Buchman and C.W.F. Everitt (Stanford)

No abstract submitted.

A New Test of the Principle of Equivalence

R.D. Reasenberg, J.D. Phillips (SAO/CfA)

We are developing a new laboratory test, in the Galilean tradition, of the Principle of Equivalence. In this test, two samples fall in a single co-moving vacuum chamber, as their vertical separation is measured with a laser gauge. The moving system, including a small getter pump, is guided by a heavy structure, built to minimize vibration. Free-fall time is about one sec, and the system recycles in about 0.3 sec. Our preliminary objective is to measure delta-g/g with an uncertainty of 10^{-11}; long term, 10^{-13}. A detailed error budget, based on a large number of falls, supports these objectives. Once a useful accuracy is achieved, we plan to test several types of matter. The experiment will also be sensitive to intermediate-range forces, such as might result from a Yukawa potential. Since the Principle of Equivalence undergirds general relativity, an apparent violation would receive considerable interest and correspondingly severe scrutiny.

This work has been supported by the Smithsonian Astrophysical Observatory.

Relativistic Effects upon Orbital Parameters

E.M. Standish (JPL)

The relativistic effect upon the precession of Mercury's perihelion is well-known, being nearly 43"/century. However, similar effects also exist among all of the planets and with different orbital elements. Using the numerical integration program of the planetary ephemeris, it is a straightforward process to determine these effects. The process is briefly described, and a table of the results is presented.

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

A Cutoff for Blackbody Radiation

M. Cahill (University of Wisconsin, Washington County)

An analysis of the statistical mechanics of spherical star clusters and the simpler case of monatomic ideal gases is known to reveal that the Michie-King globular cluster energy cutoff can be written as $\varepsilon_c \sim \ln(N)\,\overline{\varepsilon}$ where ε_c is the cutoff energy, $\overline{\varepsilon}$ is the average energy, the masses are assumed identical and where the number of cluster stars or gas particles, N, is large. The statistical methods leading to this result are shown to work for a photon gas.

The usual method of dividing phase space into cells each with Λ quantum compartments to which Bose-Einstein statistics apply is used. The resulting distribution law is $D(\Lambda - 1 + \Lambda\rho) - D(\Lambda\rho) = \varepsilon/\varepsilon_o$ where D is the logarithmic derivative of the factorial function, ε and ε_o are respectively the energy variable and an energy constant characterising the distribution and where ρ is the quantum compartment particle number density $\rho = h^3 dn/d\omega$, with $d\omega$ being the phase space volume element.

The distributions $\rho(\varepsilon/\varepsilon_o, \Lambda)$ are shown to be a one parameter family of distributions which approach the Planck law as Λ approaches ∞. For large Λ, the photon density falls to 0, where it is cut off, at $\varepsilon = \varepsilon_c \sim \ln(\Lambda)\,\overline{\varepsilon}$.

If the energy of a photon gas is finite, there must be a frequency cutoff since photon energy is proportional to frequency. It follows that Λ is finite, it is shown that $\Lambda \sim N$, and that the Planck law is an excellent approximation for its distribution except in the tail region. Also the last 2 equations imply equation 1 holds for the photon gas.

Session 9.
LATE PAPERS

S. Peale , Chair

Index

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Joe Burns 3/22/2000