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Planetary System Physics

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Summary of publications

1. Peale SJ (1998) On microlensing rates and optical depth toward the Galactic center, *Astrophys. J.* **509**, 177-191.

2. Peale SJ (1999) Newly discovered brown dwarfs not seen in microlensing timescale frequency distribution? *Astrophys. J.* **524**, L67-L70

3. Peale SJ (1999) Origin and evolution of the natural satellites, *Ann. Rev. Astron. Astrophys.* **37**, 533-602.

4. Peale SJ (1999) Probing the structure of the galaxy with microlensing (Abstract), *Bull. Am. Astron. Soc.* **31**, 1230.

5. Peale SJ (2000) Tides, *Encyclopedia of Astronomy and Astrophysics*, Institute of Physics Publishing, London. (www.ency-astro.com)

6. Lee, M.H., and Peale, S.J. (2000) The Puzzle of the Titan-Hyperion 4:3 Orbital Resonance, (Abstract) *Bull. Am. Astron. Soc.* **32**, 860.

7. Lee, M.H. (2000) On the Validity of the Coagulation Equation and the Nature of Runaway Growth, *Icarus* **143**, 74-86.

8. Lee, M.H. and Peale, S.J. (2000) Making Hyperion (Abstract), *Bull. Am. Astron. Soc.* in press.

9. Solomon, S.C....,Peale, S. J., *et al.* (2001) The MESSENGER mission to Mercury: Scientific objectives and implementation. *Plan. Space Sci.* **49**, 1445-65.

10. Lee MH (2001) A Survey of Numerical Solutions to the Coagulation Equation, *Journal of Physics A*, **34**, 10219.

11. Peale SJ (2001) Probability of detecting a planetary companion during a microlensing event, *Astrophys. J.* **552**, 889-911.

12. Lee, M.H. and S.J. Peale (2002) Dynamics and origin of the 2:1 orbital resonances of the GJ876 planets, *Astrophys. J.* **567**, 596-609.

13. Margot J, Peale SJ, Jurgens RF, Slade MA and Holin IV (2002) Planetary Interior Structure Revealed by Spin Dynamics, *Amer. Geophys. Union Fall Meeting* abstract #P22D-08.

14. Peale SJ and Lee MH (2002) A primordial origin of the Laplace relation among the Galilean Satellites, *Science* **298**, 593-97.

15. Peale SJ, Phillips RJ, Solomon SC, Smith DE and Zuber MT (2002) A procedure for determining the nature of Mercury's core, *Meteoritics & Planetary Science* **37**, 1269-1283.

16. Lee MH and Peale SJ (2003) Secular evolution of hierarchical planetary systems, *Astrophys. J.* **592**, In press.

17. Peale SJ (2003) Tidally induced volcanism, *Celest. Mech. and Dynam. Astron.* In Press.

18. Lee MH and Peale SJ (2003) Extrasolar planets and mean motion resonances, *Scientific Frontiers in Research on Extrasolar Planets*, ed. D. Deming and S. Seager (San Francisco: Astronomical Society of the Pacific), In Press.

19. Peale, SJ (2003) Comparison of a ground-based microlensing search for planets with a search from space, *Astron. J.* Under revision after review.

1. On Microlensing Event Rates and Optical Depth toward the Galactic Center, S. J. Peale (1998)

Abstract

The dependence of microlensing timescale frequency distributions and optical depth toward the Galactic center on Galactic model parameters is explored in detail for a distribution of stars consisting of the Zhao bar and nucleus and the Bahcall and Soneira double exponential disk. The high sensitivity of these two microlensing measures to the circular velocity model, velocity dispersions, bulge mass, direction of the line of sight, bar axis orientation, star spatial distribution, and the stellar mass function means no single Galaxy property can be constrained very well without constraining most of the others. However, this same sensitivity will make microlensing a powerful member of the suite of observational techniques that will eventually define the Galaxy properties. The model timescale frequency distributions are compared throughout with that determined empirically by the MACHO group. Although the MACHO empirical data are matched quite well with a nominal velocity model and with a mass function only of hydrogen-burning stars that varies as $m^{-2.2} - m^{-2.5}$ in the M-star region, uncertainties in galactic structure, kinematics, and content, together with the paucity of published microlensing

data, preclude any claim of the model representing the real world. A variation of the mass function $\sim m^{-1}$ in the M-star region obtained from recent star counts, both local and in the Galactic bulge, fails to yield a sufficient number of short timescale events compared to the MACHO data. The high sensitivity of the microlensing measures to the direction of the line of sight may mean that sufficient microlensing data to constrain the bar distribution of stars is already in hand. The procedure developed here for determining the timescale frequency distribution is particularly convenient for rapidly incorporating model changes as data from all sources continues to accumulate.

2 Newly Discovered Brown Dwarfs Not Seen in Microlensing Timescale Frequency Distribution? Peale, S. J. (1999)

Abstract

The 2 Micron All Sky Survey (2MASS) and the Deep Near-Infrared Survey (DENIS) of the southern sky have revealed a heretofore unknown population of free brown dwarfs that has extended the local mass function down to as small as 0.01 $M_\odot$. If this local proportion of brown dwarfs extends throughout the Galaxy-in particular in the Galactic bulge-one expects an increase in the predicted fraction of short-timescale microlensing events in directions toward the Galactic bulge. Zhao et al. have indicated that a mass function with 30%-60% of the lens mass in brown dwarfs is not consistent with empirical microlensing data. Here we show that even the much lower mass fraction (10%) of brown dwarfs inferred from the new discoveries appears inconsistent with the data. The added brown dwarfs do indeed increase the expected number of short-timescale events, but they appear to drive the peak in the timescale frequency distribution to timescales smaller than that observed and do not otherwise match the observed distribution. A reasonably good match to the empirical data is obtained by increasing the fraction of stars in the range $0.08 < m < 0.7$ $M_\odot$ considerably above that deduced from several star counts. However, all inferences from microlensing about the appropriate stellar mass function must be qualified by the meagerness of the microlensing data and the uncertainties in the Galactic model.

4. Probing the Structure of the Galaxy with Microlensing, S. J. Peale (1999)

Abstract

The dependence of the analysis of detailed motions within our galaxy on the distribution of mass therein warrants the vigorous pursuit of a variety of observational techniques that constrain this distribution. Hardware and software developments have led to successful programs that have detected and cataloged more than 250 gravitational lensing events, involving stellar masses and called microlensing events for historical reasons, toward the center of the galaxy, and the data continues to accumulate at an ever increasing rate. This means that microlensing can be an effective probe of galactic structure and other properties in conjunction with other techniques when the data set is sufficiently large. The microlensing optical depth tau is the probability that a ray from a distant source will pass within the Einstein ring radius R_E of an intervening star

(lens) on its way to the observer. The optical depth as a function of the direction of the line of sight is very sensitive to the distribution of stars in the galaxy—especially that in a bar-like bulge. This is demonstrated for variations of a particular galaxy model. The time scale of an event is defined as $t_E = R_E/v$ with v being the relative transverse velocity between the star being lensed (source) and the lens projected onto the lens plane, The distribution of time scale frequencies, the number of events per unit t_E as a function of t_E, depends on the mass function of the lenses, the distribution of both lenses and sources along the line of sight, and the circular velocities and velocity dispersions of the stars. Like the optical depth, the time scale frequency distributions are also sensitive to the line of sight directions. Both the optical depths and the time scale frequency distributions are routinely obtained from the growing data set. Although the dependence on so many parameters precludes definitive measures of any one galactic property by microlensing alone, constraint of some of these parameters with other techniques will allow powerful microlensing constraints on the distribution of stellar mass near the galactic plane. In particular, microlensing can detect late type dwarf stars that are invisible to all other techniques. In fact, the meager data set of about 50 events toward the galactic center that have so far been analyzed and published, imply far more M-type dwarfs than found in star counts. An empirical optical depth three times larger than that predicted from axisymmetric galactic models supports other evidence for a bar-like central bulge with the long axis pointing more or less toward the Sun. There may already be a sufficient number of events to constrain the distribution of stars in the galactic bar in considerably more detail. The variation of optical depth and time scale frequency distributions over an extensive range of parameter space defining galactic properties is demonstrated.

6. The Puzzle of the Titan-Hyperion 4:3 Orbital Resonance, M. H. Lee and S. J. Peale (2000)

Abstract

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 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 106 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.

7. On the Validity of the Coagulation Equation and the Nature of Runaway Growth, M. H. Lee (2000)

Abstract

The coagulation equation, which is widely used for modeling growth in planet formation and other astrophysical problems, is the mean-rate equation that describes the evolution of the mass spectrum of a collection of particles due to successive mergers. A numerical code that can yield accurate solutions to the coagulation equation with a reasonable number of mass bins is developed, and it is used to study the properties of solutions to the coagulation equation. We consider limiting cases of the merger rate coefficient A_{ij} for gravitational interaction, with the power-law index of the mass-radius relation $\beta = 1/3$ (for planetesimals) and $2/3$ (for stars). We classify the mass dependence of A_{ij} using the exponent λ for the merger between two particles of comparable mass, and the exponents μ and ν for the merger between a heavy particle and a light particle. For the two cases with $\nu \leq 1$ and $\lambda \leq 1$, the mass spectrum evolves in an orderly fashion. For the remaining cases, which have $\nu > 1$, we find strong numerical and analytical evidence that there are no self-consistent solutions to the coagulation equation at any time. The results for the $\nu > 1$ cases are qualitatively different from the well-known example with $A_{ij} \propto ij$. For the latter case, which is in the range $\nu \leq 1$ and $\lambda > 1$, there is an analytic solution to the coagulation equation that is valid for a finite amount of time t_0. We discuss a simplified merger problem that illustrates the qualitative differences in the solutions to the coagulation equation for the three classes of A_{ij}. Our results strongly suggest that there are two types of runaway growth. For A_{ij} with $\nu \leq 1$ and $\lambda > 1$, runaway growth starts at $t_{crit} \approx t_0$, the time at which the coagulation equation solution becomes invalid. For A_{ij} with $\nu > 1$, which include all gravitational interaction cases expected to show runaway growth, the dependence of the time t_{crit} for the onset of runaway growth on the parameters of the problem is not yet well understood, but there are indications that t_{crit} (in units of $1/(n_0 A_{11})$) may decrease slowly towards zero with increasing initial total number of particles n_0.

8. Making Hyperion, M. H. Lee and S. J. Peale (2000)

Abstract

The origin of Hyperion in the 4:3 mean-motion resonance with Titan poses special problems because of Titan's large mass and distance from Saturn. A tidal origin of the resonance, with the capture of Hyperion into the resonance as the orbit of Titan was expanded by tides, suffers from the requirement that the dissipation parameter Q of Saturn for Titan induced tides must be much less than the lower bound set by the proximity of Mimas to Saturn if Titan's orbit was to expand significantly. We investigate the formation of Hyperion through the accretion of satellitesimals using N-body simulations. We are able to form Hyperion and leave it in the 4:3 resonance with essentially its current orbital properties if (1) the gradient of the surface mass density of the disk of particles and gas is relatively steep (r^{-3}), (2) the time over which the mass and eccentricity of Titan grow to their current values is relatively long (8 x 105 Titan orbital periods), and (3) no particles are added to the outside of the disk. These conditions may be real constraints on the properties of the disk that formed the Saturnian satellite system. The simulations are performed using the symplectic integrator SyMBA, with different imposed rates of growth of Titan's mass and eccentricity and gas drag from an accompanying gas disk (the total composition of the particle and gas disk being solar). There are initially ≈ 1100 particles in an annulus from approximately 1.1 to 1.45 Titan orbital radius, with the surface mass density $\sim r^{-n}$, where $1 \leq n \leq 3$. The surface density of the disk at Hyperion's current orbital radius specifies the total initial disk mass. Although gas drag can bring more satellitesimals into the vicinity of resonances, accretion does not generally occur within any of the resonances because satellitesimal interaction is sufficiently strong to scatter particles out of the resonances. However, gas drag seems to be a necessary process in the scenario to allow orbital decay and capture into the resonance after most of the accretion is complete. Scenarios with an initial surface density in the disk that varies as r^{-1} and/or the addition of particles near the outer edge of the initial disk to simulate particles migrating from further distances through gas drag lead to the last large embryo(s) ending up in a resonance outside the 4:3 resonance, with the 3:2 resonance being strongly preferred.

9. The MESSENGER mission to Mercury: scientific objectives and implementation, Solomon, Sean C.; McNutt, Ralph L.; Gold, Robert E.; Acua, Mario H.; Baker, Daniel N.; Boynton, William V.; Chapman, Clark R.; Cheng, Andrew F.; Gloeckler, George; Head, James W., III; Krimigis, Stamatios M.; McClintock, William E.; Murchie, Scott L.; Peale, Stanton J.; Phillips, Roger J.; Robinson, Mark S.; Slavin, James A.; Smith, David E.; Strom, Robert G.; Trombka, Jacob I.; Zuber, Maria T. (2001)

Abstract

Mercury holds answers to several critical questions regarding the formation and evolution of the terrestrial planets. These questions include the origin of Mercury's anomalously high ratio of metal to silicate and its implications for planetary accretion processes, the nature of Mercury's geological evolution and interior cooling history, the mechanism of global magnetic field generation, the state of Mercury's core, and the processes controlling volatile species in Mercury's polar deposits, exosphere, and magnetosphere. The MErcury Surface, Space ENvironment, GEochemistry, and Ranging

(MESSENGER) mission has been designed to fly by and orbit Mercury to address all of these key questions. After launch by a Delta 2925H-9.5, two flybys of Venus, and two flybys of Mercury, orbit insertion is accomplished at the third Mercury encounter. The instrument payload includes a dual imaging system for wide and narrow fields-of-view, monochrome and color imaging, and stereo; X-ray and combined gamma-ray and neutron spectrometers for surface chemical mapping; a magnetometer; a laser altimeter; a combined ultraviolet-visible and visible-near-infrared spectrometer to survey both exospheric species and surface mineralogy; and an energetic particle and plasma spectrometer to sample charged species in the magnetosphere. During the flybys of Mercury, regions unexplored by Mariner 10 will be seen for the first time, and new data will be gathered on Mercury's exosphere, magnetosphere, and surface composition. During the orbital phase of the mission, one Earth year in duration, MESSENGER will complete global mapping and the detailed characterization of the exosphere, magnetosphere, surface, and interior.

10. A Survey of Numerical Solutions to the Coagulation Equation, M. H. Lee (2001).

Abstract

We present the results of a systematic survey of numerical solutions to the coagulation equation for a rate coefficient of the form $A_{ij} \propto (i^\mu j^\nu + i^\nu j^\mu)$ and monodisperse initial conditions. The results confirm that there are three classes of rate coefficients with qualitatively different solutions. For $\nu \leq 1$ and $\lambda = \mu + \nu \leq 1$, the numerical solution evolves in an orderly fashion and tends toward a self-similar solution at large time t. The properties of the numerical solution in the scaling limit agree with the analytic predictions of van Dongen and Ernst. In particular, for the subset with $\mu > 0$ and $\lambda < 1$, we disagree with Krivitsky and find that the scaling function approaches the analytically predicted power-law behavior at small mass, but in a damped oscillatory fashion that was not known previously. For $\nu \leq 1$ and $\lambda > 1$, the numerical solution tends toward a self-similar solution as t approaches a finite time t_0. The mass spectrum n_k develops at t_0 a power-law tail $n_k \propto k^{-\tau}$ at large mass that violates mass conservation, and runaway growth/gelation is expected to start at $t_{crit} = t_0$ in the limit the initial number of particles $n_0 \to \infty$. The exponent τ is in general less than the analytic prediction $(\lambda + 3)/2$, and $t_0 = K/[(\lambda - 1)n_0 A_{11}]$ with $K = 1$–2 if $\lambda \gtrsim 1.1$. For $\nu > 1$, the behaviors of the numerical solution are similar to those found in a previous paper by us. They strongly suggest that there are no self-consistent solutions at any time and that runaway growth is instantaneous in the limit $n_0 \to \infty$. They also indicate that the time t_{crit} for the onset of runaway growth decreases slowly toward zero with increasing n_0.

11. Probability of detecting a planetary companion during a microlensing event, S. J. Peale (2001).

Abstract

The probability of detecting a planetary companion of a lensing star during a microlensing event toward the Galactic center when the planet-star mass ratio is 0.001 is shown to have a maximum exceeding 20% for a distribution of source-lens impact parameters that is determined by the efficiency of detection, and a maximum exceeding 10% for a uniform distribution of impact parameters. This probability is based on the use of 2 meter telescopes with 60 second integrations in I-band with frequent photometry throughout the duration of an ongoing event. The probability varies as $\sqrt{m/M}$, where m/M is the planet-star mass ratio. A planet is assumed detectable if the perturbation of the light curve exceeds $2/(S/N)$ for a significant number of data points, where S/N is the signal-to-noise ratio. The probability peaks at a planetary semimajor axis a that is close to the mean Einstein ring radius along the line of sight, and remains significant for $0.6 \leq a \leq 10$ AU. The probability is averaged over the distribution of the projected position of the planet onto the lens plane, over the lens mass function, over the distribution of impact parameters, over the distribution of lens and sources along the line of sight and over the I-band luminosity function adjusted for the source distance. The probability for a particular impact parameter and particular source I magnitude but averaged over remaining degenerate parameters is also derivable from the analysis. The high probabilities and the promise of gaining statistics rapidly on the frequency of planets in long period orbits encourages the expansion of ground based microlensing searches for planets with enhanced capabilities.

12. Dynamics and Origin of the 2:1 Orbital Resonances of the GJ876 Planets, M. H. Lee and S. J. Peale (2002)

Abstract

The discovery by Marcy et al. (2001) of two planets in 2:1 orbital resonance about the star GJ876 has been supplemented by a dynamical fit to the data by Laughlin & Chambers (2001) which places the planets in coplanar orbits deep in three resonances at the 2:1 mean-motion commensurability. The selection of this almost singular state by the dynamical fit means that the resonances are almost certainly real, and with the small amplitudes of libration of the resonance variables, indefinitely stable. Several unusual properties of the 2:1 resonances are revealed by the GJ876 system. The libration of both lowest order mean-motion resonance variables and the secular resonance variable, $\theta_1 = \lambda_1 - 2\lambda_2 + \varpi_1$, $\theta_2 = \lambda_1 - 2\lambda_2 + \varpi_2$, and $\theta_3 = \varpi_1 - \varpi_2$, about $0°$ (where $\lambda_{1,2}$ are the mean longitudes of the inner and outer planet and $\varpi_{1,2}$ are the longitudes of periapse) differs from the familiar geometry of the Io-Europa pair, where θ_2 and θ_3 librate about $180°$. By considering the condition that $\dot{\varpi}_1 = \dot{\varpi}_2$ for stable simultaneous librations of θ_1 and θ_2, we show that the GJ876 geometry results because of the large orbital eccentricities e_i, whereas the very small eccentricities in the Io-Europa system lead to the latter's geometry. Surprisingly, the GJ876 configuration, with θ_1, θ_2, and θ_3 all librating, remains stable for e_1 up to 0.86 and for amplitude of libration of θ_1 approaching $45°$ with the current eccentricities — further supporting the indefinite stability of the existing system.

Any process that drives originally widely separated orbits toward each other could result in capture into the observed resonances at the 2:1 commensurability. We find that forced inward migration of the outer planet of the GJ876 system results in certain capture into the observed resonances if initially $e_1 \lesssim 0.06$ and $e_2 \lesssim 0.03$ and the migration rate $|\dot{a}_2/a_2| \lesssim 3 \times 10^{-2}(a_2/AU)^{-3/2}/yr$. Larger eccentricities lead to likely capture into higher order resonances before the 2:1 commensurability is reached. The planets are sufficiently massive to open gaps in the nebular disk surrounding the young GJ876 and to clear the disk material between them, and the resulting planet-nebular interaction typically forces the outer planet to migrate inward on the disk viscous time scale, whose inverse is about three orders of magnitude less than the above upper bound on $|\dot{a}_2/a_2|$ for certain capture. If there is no eccentricity damping, eccentricity growth is rapid with continued migration within the resonance, with e_i exceeding the observed values after a further reduction in the semi-major axes a_i of only 7%. With eccentricity damping $\dot{e}_i/e_i = -K|\dot{a}_i/a_i|$, the eccentricities reach equilibrium values that remain constant for arbitrarily long migration within the resonances. The equilibrium eccentricities are close to the observed eccentricities for $K \approx 100$ if there is migration and damping of the outer planet only, but for $K \approx 10$ if there is also migration and damping of the inner planet. This result is independent of the magnitude or functional form of the migration rate $\dot{a}_i$ as long as $\dot{e}_i/e_i = -K|\dot{a}_i/a_i|$. Although existing analytic estimates of the effects of planet-nebula interaction are consistent with this form of eccentricity damping for certain disk parameter values, it is as yet unclear that such interaction can produce the large value of K required to obtain the observed eccentricities. The alternative eccentricity damping by tidal dissipation within the star or the planets is completely negligible, so the observed dynamical properties of the GJ876 system may require an unlikely fine tuning of the time of resonance capture to be near the end of the nebula lifetime.

13. Planetary Interior Structure Revealed by Spin Dynamics, Margot, J.; Peale, S. J.; Jurgens, R. F.; Slade, M. A.; Holin, I. V. (2002)

Abstract

The spin state of a planet depends on the distribution of mass within the interior, gradual and discrete changes in its moments of inertia, dissipation mechanisms at the surface and below, and external torques. Detailed measurements of the spin dynamics can therefore reveal much about planetary interior structure, interactions at the core-mantle and atmosphere-surface boundaries, and mass redistribution events. Studies of the spin precession, polar wobble, and length of day variations have been used to determine Earth's moments of inertia and rigidity and to study the effects of atmospheric angular momentum changes, post-glacial rebound, and large earthquakes. In planetary investigations the spin measurements are particularly important because other means of constraining interior properties require in-situ or orbiting sensors (e.g. seismometers, magnetometers, and Doppler tracking of spacecraft). Here we describe the successful implementation of a new Earth-based radar technique (Holin, 1992) that provides spin state measurements with unprecedented accuracy. Our first observations

were designed to characterize Mercury's core. Peale (1976) showed that the measurement of four quantities (the obliquity of the planet, the amplitude of its longitude librations, and the second-degree gravitational harmonics) are sufficient to determine the size and state of Mercury's core. The existence of a molten core would place strong constraints on the thermal and rotational histories of the planet, with profound implications for the composition and rotation state of the planet at the time of formation. A solid core would have a fundamental impact on theories of planetary magnetic field generation. We observed Mercury with the Goldstone radar and the Green Bank Telescope in May-June 2002. We illuminated the planet with a monochromatic signal, recorded the scattered power at the two antennas, and cross-correlated the echoes in the time domain. We obtained strong correlations which directly constrain the instantaneous spin rate and orientation. Our measurements provide the first experimental proof that Mercury is in a Cassini state, a three-order of magnitude improvement in the knowledge of the spin orientation, a measurement of the obliquity which places new constraints on the moments of inertia, and an upper-limit to the amplitude of the longitude librations which constrains interior properties. The IAU-recommended values for the spin orientation of Mercury have not changed since the Mariner days (Davies et al., 1980). The new spin solution can be used to improve the geodetic control of the Mariner 10 images, a task that was pioneered and perfected by Merton G. Davies (1917-2001).

14. A primordial origin of the Laplace relation among the Galilean Satellites, S. J. Peale and M. H. Lee (2002)

Abstract

Understanding the origin of the orbital resonances of the Galilean satellites of Jupiter will constrain the longevity of the extensive volcanism on Io, may explain a liquid ocean on Europa, and may guide studies of the dissipative properties of stars and Jupiter-like planets. The differential migration of the newly formed Galilean satellites due to interactions with a circumjovian disk can lead to the primordial formation of the Laplace relation $n_1 - 3n_2 + 2n_3 = 0$, where the n_i are the mean orbital angular velocities of Io, Europa, and Ganymede, respectively. This contrasts with the formation of the resonances by differential expansion of the orbits from tidal torques from Jupiter.

15. A procedure for determining the nature of Mercury's core, S. J. Peale, R. J. Phillips, S. C. Solomon, D. E. Smith, and M. T. Zuber (2002)

Abstract

We review the assertion that the precise measurement of the second degree gravitational harmonic coefficients, the obliquity, and the amplitude of the physical libration in longitude, C_{20}, C_{22}, θ, and ϕ_0, for Mercury are sufficient to determine whether or not Mercury has a molten core. The conditions for detecting the signature of the molten core are that such a core not follow the 88–day physical libration of the mantle induced by periodic solar torques, but that it does follow the 250,000–year precession

of the spin axis that tracks the orbit precession within a Cassini spin state. These conditions are easily satisfied if the coupling between the liquid core and solid mantle is viscous in nature. The alternative coupling mechanisms of pressure forces on irregularities in the core–mantle boundary (CMB), gravitational torques between an axially asymmetric mantle and an assumed axially asymmetric solid inner core, and magnetic coupling between the conducting molten core and a conducting layer in the mantle at the CMB are shown for a reasonable range of assumptions not to frustrate the first condition while making the second condition more secure. Simulations have shown that the combination of spacecraft tracking and laser altimetry during the planned MESSENGER orbiter mission to Mercury will determine C_{20}, C_{22}, and θ to better than 1% and ϕ_0 to better than 8%—sufficient precision to distinguish a molten core and constrain its size. The possible determination of the latter two parameters to 1% or less with Earth–based radar experiments and MESSENGER determination of C_{20} and C_{22} to 0.1% would lead to a maximum uncertainty in the ratio of the moment of inertia of the mantle to that of the whole planet, C_m/C, of about 2% with comparable precision in characterizing the extent of the molten core.

16. Secular evolution of hierarchical planetary systems, M. H. Lee and S. J. Peale (2003)

Abstract

We investigate the dynamical evolution of coplanar hierarchical two-planet systems where the ratio of the orbital semimajor axes $\alpha = a_1/a_2$ is small. Hierarchical two-planet systems are likely to be ubiquitous among extrasolar planetary systems. We show that the orbital parameters obtained from a multiple Kepler fit to the radial velocity variations of a host star are best interpreted as Jacobi coordinates and that Jacobi coordinates should be used in any analyses of hierarchical planetary systems. An approximate theory that can be applied to coplanar hierarchical two-planet systems with a wide range of masses and orbital eccentricities is the octupole-level secular perturbation theory, which is based on an expansion to order α^3 and orbit-averaging. It reduces the coplanar problem to one degree of freedom, with e_1 (or e_2) and $\varpi_1 - \varpi_2$ as the relevant phase-space variables (where $e_{1,2}$ are the orbital eccentricities of the inner and outer orbits and $\varpi_{1,2}$ are the longitudes of periapse). The octupole equations show that if the ratio of the maximum orbital angular momenta, $\lambda = L_1/L_2 \approx (m_1/m_2)\alpha^{1/2}$, for given semimajor axes is approximately equal to a critical value λ_{crit}, then libration of $\varpi_1 - \varpi_2$ about either 0° or 180° is almost certain, with possibly large amplitude variations of both eccentricities. From a study of the HD 168443 and HD 12661 systems and their variants using both the octupole theory and direct numerical orbit integrations, we establish that the octupole theory is highly accurate for systems with $\alpha \lesssim 0.1$ and reasonably accurate even for systems with α as large as 1/3, provided that α is not too close to a significant mean-motion commensurability or above the stability boundary. The HD 168443 system is not in a secular resonance and its $\varpi_1 - \varpi_2$ circulates. The HD 12661 system is the first extrasolar planetary system found to have $\varpi_1 - \varpi_2$ librating about 180°. The secular resonance means that the lines of apsides of the two orbits are on average anti-aligned, although the amplitude of libration of

$\varpi_1 - \varpi_2$ is large. The libration of $\varpi_1 - \varpi_2$ and the large-amplitude variations of both eccentricities in the HD 12661 system are consistent with the analytic results on systems with $\lambda \approx \lambda_{\rm crit}$. The evolution of the HD 12661 system with the best-fit orbital parameters and $\sin i = 1$ (i is the inclination of the orbital plane from the plane of the sky) is affected by the close proximity to the 11:2 mean-motion commensurability, but small changes in the orbital period of the outer planet within the uncertainty can result in configurations that are not affected by mean-motion commensurabilities. The stability of the HD 12661 system requires $\sin i > 0.3$.

17. Tidally induced volcanism, S. J. Peale (2003)

(This paper is a review derived from an invited paper presented at IAU Colloquium 189 in Nanjing, China in Sept. 2002)

Abstract

The dissipation of tidal energy causes the ongoing silicate volcanism on Jupiter's satellite, Io, and cryovolcanism almost certainly has resurfaced parts of Saturn's satellite, Enceladus, at various epochs distributed over the latter's history. The maintenance of tidal dissipation in Io and the occurrence of the same on Enceladus depends crucially on the maintenance of the respective orbital eccentricities by the existence of mean motion resonances with nearby satellites. A formation of the resonances among the Galilean satellites by differential expansion of the satellite orbits from tides raised on Jupiter by the satellites means the onset of the volcanism on Io could be relatively recent. If, on the other hand, the resonances formed by differential migration from resonant interactions of the satellites with the disk of gas and particles from which they formed, Io would have been at least intermittently volcanically active throughout its history. Either means of assembling the Galilean satellite resonances lead to the same constraint on the dissipation function of Jupiter $Q_J \lesssim 10^6$, where the currently high heat flux from Io seems to favor episodic heating as Io's eccentricity periodically increases and decreases. Either of two models might account for sufficient tidal dissipation in the icy satellite, Enceladus, to cause at least occasional cryovolcanism over much of its history. However, both models are assumption dependent and not secure, so uncertainty remains on how tidal dissipation resurfaced Enceladus.

18. Extrasolar planets and mean motion resonances, M. H. Lee and S. J. Peale (2002)

Abstract

The 2:1 orbital resonances of the GJ876 system can be easily established by the differential planet migration due to planet-nebula interaction. Significant eccentricity damping is required to produce the observed orbital eccentricities. The geometry of the GJ 876 resonance configuration differs from that of the Io-Europa pair, and this difference is due to the magnitudes of the eccentricities involved. We show that a large variation in the configuration of 2:1 and 3:1 resonances and, in particular, asymmetric librations can be expected among future discoveries.

19. Comparison of a ground-based microlensing search for planets with a search from space, S. J. Peale (2003)

Abstract

We compare a space-based microlensing search for planets, with a ground based microlensing search originally proposed by D. Tytler (Beichman, *et al.* 1996). Perturbations of microlensing light curves when the lens star has a planetary companion are sought by one wide angle survey telescope and an array of three or four followup narrow angle telescopes distributed in longitude that follow events with high precision, high time resolution photometry. Alternative ground based programs are considered briefly. With the four 2 meter telescopes distributed in longitude in the southern hemisphere in the Tytler proposal, observational constraints on a ground-based search for planets during microlensing events toward the center of the galaxy are severe. Probably less than 100 events could be monitored per year with high precision, high time resolution photometry with only about 42% coverage on the average regardless of how many events were discovered by the survey telescope. Statistics for the occurrence and properties for Jupiter-mass planets would be meaningful but relatively meager four years after the program was started, and meaningful statistics for Earth-mass planets would be non existent. In contrast, the 14,500 events in a proposed 4 year space based program (GEST = Galactic Exoplanet Survey Telescope) would yield very sound statistics on the occurrence, masses and separations of Jupiter-mass planets, and significant constraints on similar properties for Earth-mass planets. The significance of the Jupiter statistics would be to establish the frequency of planetary systems like our own, where terrestrial planets could exist inside the orbits of the giants.