LONG-TERM DYNAMICS OF SMALL BODIES IN THE SOLAR SYSTEM

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FINAL REPORT

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Final Report for NASA Planetary Geology and Geophysics Grant NAG5-10365 Matthew J. Holman

As part of the NASA Planetary Geology and Geophysics program Prof. Norm Murray (CITA) and I have been conducting investigations of the long-term dynamics of small bodies in the outer solar system. This grant, and its predecessor NAG5-7761, supported travel for collaboration by the Investigators and also supports Murray during an annual one month visit to the CfA for further collaboration. In the course of this grant we made a number of advances in solar system dynamics. For example, we developed an analytic model for the origin and consequence of chaos associated with three-body resonances in the asteroid belt. This has been shown to be important for the delivery of near Earth objects. We later extended this model to three- body resonances among planets. We were able to show that the numerically identified chaos among the outer planets results from a three-body resonance involving Jupiter, Saturn, and Uranus. The resulting paper was awarded the 1999 Newcomb Cleveland award from the AAAS. This award singles out one paper published in Science each year for distinction.

This grant has also supported, in part, my participate in other solar system dynamics projects. The results from those collaborations are also listed.

Publications related to this grant:

1. Holman MJ, Murray NW. 2005. "The Use of Transit Timing to Detect Terrestrial-Mass Extrasolar Planets," *Science*, **307**, 1288-1291.

   Future surveys for transiting extrasolar planets are expected to detect hundreds of jovian-mass planets and tens of terrestrial-mass planets. For many of these newly discovered planets, the intervals between successive transits will be measured with an accuracy of 0.1 to 100 minutes. We show that these timing measurements will allow for the detection of additional planets in the system (not necessarily transiting) by their gravitational interaction with the transiting planet. The transit-time variations depend on the mass of the additional planet, and in some cases terrestrial-mass planets will produce a measurable effect. In systems where two planets are seen to transit, the density of both planets can be determined without radial-velocity observations.

2. Moran SM, Kuchner MJ, Holman MJ. 2004. "The Dynamical Influence of a Planet at Semimajor Axis 3.4 AU on Dust around ϵ Eridani," *ApJ*, **612**, 1163-1170.

   Precise Doppler experiments suggest that a massive (msini=0.86MJ) planet orbits at semimajor axis a=3.4 AU around ϵ Eri, a nearby star with a massive debris disk. The dynamical perturbations from such a planet would mold the distribution of dust around this star. We numerically integrated the orbits of dust grains in this system to predict the central dust-cloud structure. For a supply of grains that begin in low-inclination, low-eccentricity orbits at 15 AU, the primary feature of the dust distribution is a pair of dense clumps containing dust particles trapped in mean-motion resonances of the form n:1. These clumps appear to revolve around the star once every two planet revolutions. Future observations with the IRAM Plateau de Bure Interferometer, the Submillimeter Array (SMA), or the Atacama Large Millimeter Array (ALMA) could detect these clumps, confirming the existence of the planet and revealing its location.

3. Franklin FA, Lewis NK, Soper PR, Holman MJ. 2004. "Hilda Asteroids as Possible Probes of Jovian Migration," *AJ*, **128**, 1391-1406.

   We show that the peculiar eccentricity distribution of the Hilda asteroids, objects that librate at the 3:2 mean motion resonance with Jupiter, as well as their distribution about the resonance itself, can be nicely reproduced from captured field asteroids if Jupiter has migrated sunward by about 0.45 AU over a time greater than 100,000 years. The latter is a lower limit and longer times are more likely, while the former quantity depends to some degree on the initial eccentricity distribution, but a fit to the observations fails unless it lies in the range of 0.4 to about 0.5 AU, where the lower value is particularly well established. We have included some integrations comparable to the solar system's age to show that many Hilda orbits with a broad range of proper eccentricity, ep, and, most importantly, those with $e_p < 0.10$, are stable over such times. The observed fact that there are very few Hildas with $e_p < 0.10$ strengthens the case for a migration greater than about 0.4 AU because, as we discuss, processes intimately linked with it eliminate most of the low-ep bodies automatically. A relatively much smaller but not negligible number of orbits at the 4:3 resonance are similarly stable, and one possible reason needing further investigation for the near-absence of real bodies of any eccentricity there (one asteroid) might be traced to the passage of Jupiter and Saturn through a 5:2 orbital resonance.

4. Winn JN, Holman MJ, Johnson JA, Stanek KZ, Garnavich PM. 2004. "KH 15D: Gradual Occultation of a Pre-Main-Sequence Binary," *ApJ* **603**, L45-L48.

   We propose that the extraordinary "winking star" KH 15D is an eccentric pre-main-sequence binary that is gradually being occulted by an opaque screen. This model accounts for the periodicity, depth, duration, and rate of growth of the modern eclipses; the historical light curve from photographic plates; and the existing radial velocity measurements. It also explains the rebrightening events that were previously observed during eclipses and the subsequent disappearance of these events. We predict the future evolution of the system and its full radial velocity curve. Given the small velocity of the occulting screen relative to the center of mass of the binary, the screen is probably associated with the binary and may be the edge of a precessing circumbinary disk.

5. Kuchner MJ and Holman MJ. 2003. "The Geometry of Resonant Signatures in Debris Disks with Planets," *ApJ* **588**, 1110-1120.

   Using simple geometrical arguments, we paint an overview of the variety of resonant structures a single planet with moderate eccentricity (e¡ 0.6) can create in a dynamically cold, optically thin dust disk. This overview may serve as a key for interpreting images of perturbed debris disks and inferring the dynamical properties of the planets responsible for the perturbations. We compare the resonant geometries found in the solar system dust cloud with observations of dust clouds around Vega, Epsilon Eridani, and Fomalhaut.

6. Wilner DJ, Holman MJ, Kuchner MJ, Ho PTP. 2002. "Structure in the Dusty Debris around Vega," *ApJ* **569**, L115-L119.

   We present images of the Vega system obtained with the IRAM Plateau de Bure interferometer at a 1.3 mm wavelength with submillijansky sensitivity and 2.5" resolution (about 20 AU). These observations clearly detect the stellar photosphere and two dust emission peaks offset from the star by 9.5" and 8.0" to the northeast and southwest, respectively. These offset emission peaks are consistent with the barely resolved structure visible in previous submillimeter images, and they account for a large fraction of the dust emission. The presence of two dust concentrations at the observed locations is plausibly explained by the dynamical influence of an unseen planet of a few Jupiter masses in a highly eccentric orbit that traps dust in principal mean motion resonances. Based on observations carried out with the IRAM Plateau de Bure Interferometer. IRAM is supported by the Instut Nationale des Sciences de L'Univers, CNRS (France), Max-Plank-Gesellschaft (Germany), and Instituto Geogrfico Nacional (Spain).

7. Kuchner MJ, Brown ME, Holman M. 2002. "Long-Term Dynamics and the Orbital Inclinations of the Classical Kuiper Belt Objects," *AJ* **124**, 1221-1230.

   We numerically integrated the orbits of 1458 particles in the region of the classical Kuiper belt (41 AU $\leq a \leq$ 47 AU) to explore the role of dynamical instabilities in sculpting the inclination distribution of the classical Kuiper belt objects (KBOs). We find that the selective removal of low-inclination objects by overlapping secular resonances acts to raise the mean inclination of the surviving population of particles over 4 billion yr of interactions with Jupiter, Saturn, Uranus, and Neptune, though these long-term dynamical effects do not themselves appear to explain the discovery of KBOs with inclinations near 30 degrees. Our integrations also imply that after 3 billion yr of interaction with the massive planets, high-inclination KBOs more efficiently supply Neptune-encountering objects, the likely progenitors of short-period comets, Centaurs, and scattered KBOs. The secular resonances at low inclinations may indirectly cause this effect by weeding out objects unprotected by mean motion resonances during the first 3 billion yr.

8. Murray N, Paskowitz M, Holman M. 2001. "Eccentricity Evolution of Resonant Migrating Planets," *ApJ* **565**, 608-620.

   We examine the eccentricity evolution of a system of two planets locked in a mean motion resonance, in which either the outer or both planets lose energy and angular momentum. The sink of energy and angular momentum could be a gas or planetesimal disk. We analytically calculate the eccentricity damping rate in the case of a single planet migrating through a planetesimal disk. When the planetesimal disk is cold (the average eccentricity is much less than 1), the circularization time is comparable to the inward migration time, as previous calculations have found for the case of a gas disk. If the planetesimal disk is hot, the migration time can be an order of magnitude shorter. We show that the eccentricity of both planetary bodies can grow to large values, particularly if the inner body does not directly exchange energy or angular momentum with the disk. We present the results of numerical integrations of two migrating resonant planets showing rapid growth of eccentricity. We also present integrations in which a Jupiter-mass planet is forced to migrate inward through a system of 5-10 roughly Earth-mass planets. The migrating planet can eject or accrete the smaller bodies; roughly 5central star. The results are discussed in the context of the currently known extrasolar planetary systems.

9. Murray N, and Holman M. 2001. "The Role of Chaotic Resonances in the Solar System," *Nature* **410**, 773-779.

   Our understanding of the Solar System has been revolutionized over the past decade by the finding that the orbits of the planets are inherently chaotic. In extreme cases, chaotic motions can change the relative positions of the planets around stars, and even eject a planet from a system. Moreover, the spin axis of a planet-Earths spin axis regulates our seasons-may evolve chaotically, with adverse effects on the climates of otherwise biologically interesting planets. Some of the recently discovered extrasolar planetary systems contain multiple planets, and it is likely that some of these are chaotic as well.

10. Lecar M, Franklin FA, Holman MJ, Murray NW. 2001. "Chaos in the solar system," 2001. *Annual Rev. Astron. Astrophys* **39**, 581-631.

The physical basis of chaos in the solar system is now better understood: In all cases investigated so far, chaotic orbits result from overlapping resonances. Perhaps the clearest examples are found in the asteroid belt. Overlapping resonances account for its Kirkwood gaps and were used to predict and find evidence for very narrow gaps in the outer belt. Further afield, about one new "short-period" comet is discovered each year. They are believed to come from the "Kuiper Belt" (at 40 AU or more) via chaotic orbits produced by mean-motion and secular resonances with Neptune. Finally, the planetary system itself is not immune from chaos. In the inner solar system, overlapping secular resonances have been identified as the possible source of chaos. For example, Mercury, in 1012 years, may suffer a close encounter with Venus or plunge into the Sun. In the outer solar system, three-body resonances have been identified as a source of chaos, but on an even longer time scale of 109 times the age of the solar system. On the human time scale, the planets do follow their orbits in a stately procession, and we can predict their trajectories for hundreds of thousands of years. That is because the mavericks, with shorter instability times, have long since been ejected. The solar system is not stable; it is just old!

11. Quillen AC, Holman M. 2000. "Production of Star-grazing and Star-impacting Planetesimals via Orbital Migration of Extrasolar Planets," *AJ* **119**, 397-402.

    During orbital migration of a giant extrasolar planet via ejection of planetesimals (as studied by Murray et al. in 1998), inner mean-motion resonances can be strong enough to cause planetesimals to graze or impact the star. We integrate numerically the motions of particles which pass through the 3:1 or 4:1 mean-motion resonances of a migrating Jupiter-mass planet. We find that many particles can be trapped in the 3:1 or 4:1 resonances and pumped to high enough eccentricities that they impact the star. This implies that for a planet migrating a substantial fraction of its semimajor axis, a fraction of its mass in planetesimals could impact the star. This process may be capable of enriching the metallicity of the star at a time when the star is no longer fully convective. Upon close approaches to the star, the surfaces of these planetesimals will be sublimated. Orbital migration should cause continuing production of evaporating bodies, suggesting that this process should be detectable with searches for transient absorption lines in young stars. The remainder of the particles will not impact the star but can be ejected subsequently by the planet as it migrates further inward. This allows the planet to migrate a substantial fraction of its initial semimajor axis by ejecting planetesimals.

12. Murray N, Holman M. 1999. "The origin of chaos in outer solar system," *Science* **283**, 1877-1881.

Classical analytic theories of the solar system indicate that it is stable, but numerical integrations suggest that it is chaotic. This disagreement is resolved by a new analytic theory. The theory shows that the chaos among the Jovian planets results from the overlap of the components of a mean motion resonance among Jupiter, Saturn, and Uranus, and provides rough estimates of the Lyapunov time (10 million years) and the dynamical lifetime of Uranus (10^{18} years). The Jovian planets must have entered the resonance after all the gas and most of the planetesimals in the protoplanetary disk were removed.

13. Rauch K, Holman M. 1999. "Dynamical chaos in the Wisdom-Holman integrator: origins and solutions," *AJ* **117**, 1087-1102.

    We examine the nonlinear stability of the Wisdom-Holman (WH) symplectic mapping applied to the integration of perturbed, highly eccentric (e 0.9) two-body orbits. We find that the method is unstable and introduces artificial chaos into the computed trajectories for this class of problems, unless the step size chosen is small enough that periapse is always resolved, in which case the method is generically stable. This "radial orbit instability" persists even for weakly perturbed systems. Using the Stark problem as a fiducial test case, we investigate the dynamical origin of this instability and argue that the numerical chaos results from the overlap of step-size resonances; interestingly, for the Stark problem many of these resonances appear to be absolutely stable. We similarly examine the robustness of several alternative integration methods: a time-regularized version of the WH mapping suggested by Mikkola; the potential-splitting (PS) method of Duncan, Levison, Lee; and two original methods incorporating approximations based on Stark motion instead of Keplerian motion (compare Newman et al.). The two fixed point problem and a related, more general problem are used to conduct a comparative test of the various methods for several types of motion. Among the algorithms tested, the time-transformed WH mapping is clearly the most efficient and stable method of integrating eccentric, nearly Keplerian orbits in the absence of close encounters. For test particles subject to both high eccentricities and very close encounters, we find an enhanced version of the PS method-incorporating time regularization, force-center switching, and an improved kernel function-to be both economical and highly versatile. We conclude that Stark-based methods are of marginal utility in N-body type integrations. Additional implications for the symplectic integration of N-body systems are discussed.

14. Holman M, Wiegert P. 1999. "Long-term stability of planets in binary systems," *AJ* **117**, 621-628.

    A simple question of celestial mechanics is investigated: in what regions of phase space near a binary system can planets persist for long times? The planets are taken to be test particles moving in the field of an eccentric binary system. A range of values of the binary eccentricity and mass ratio is studied, and both the case of planets orbiting close to one of the stars, and that of planets outside the binary orbiting the systems center of mass, are examined. From the results, empirical expressions are developed for both (1) the largest orbit around each of the stars and (2) the smallest orbit around the binary system as a whole, in which test particles survive the length of the integration (10^4 binary periods). The empirical expressions developed, which are roughly linear in both the mass ratio mu and the binary eccentricity e, are determined for the range 0.0=e=0.7-0.8 and 0.1=mu=0.9 in both regions and can be used to guide searches for planets in binary systems. After considering the case of a single low-mass planet in binary systems, the stability of a mutually interacting system of planets orbiting one star of a binary system is examined, though in less detail.

15. Murray N, Holman M, Potter M. 1998. "On the origin of chaos in the asteroid belt," *AJ* **116**, 2583-2589.

We consider the effect of gravitational perturbations from Jupiter on the dynamics of asteroids, when Jupiter is itself perturbed by Saturn. The presence of Saturn introduces a number of additional frequencies into Jupiters orbit. These frequencies in turn produce chaos in narrow regions on either side of the chaotic zones associated with the mean motion resonances between the asteroids and Jupiter. The resonant arguments of these three-body resonances contain the longitudes of Jupiter and the asteroid together with either the secular frequency g_6, or the longitude of Saturn. Resonances involving the longitude of Saturn are analogs of the Laplace resonance in the Jovian satellite system. We show that many three-body resonances involving the longitude of Saturn are chaotic. We give simple expressions for the width of the chaotic region and the associated Lyapunov time. In some cases the chaos can produce a diffusive growth in the eccentricity of the asteroid that leads to ejection of the asteroid on times shorter than the age of the solar system. We give simple estimates for the diffusion time. Finally, we present the results of numerical integrations testing the theory.