Final Report

The Stability of Orbital Configurations and the Ultimate Configurations of Planetary and Satellite Systems, Jack J. Lissauer
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1) Dynamical Evolution of the Earth-Moon Progenitors

Substantial evidence indicates that the Earth-Moon system formed about 100 Myr after the oldest meteorites and that the inner Solar System had five terrestrial planets for several tens of millions of years before the hypothesized Moon-forming giant impact. We wanted to know if it is plausible that the Earth-Moon progenitors collided after 8 - 200 Myr, forming a system "similar to" the Solar System. To test this hypothesis, we have integrated the Solar System with the Earth-Moon system replaced by two bodies in heliocentric orbits between Venus and Mars. We modified the SyMBA code (Duncan et al. 1998) to integrate our input systems and to calculate parameters of the impact if a collision occurs. If a collision occurs, the integrations tell us which two bodies collide and the time of the collision. We also determine the angular momentum deficit (AMD) of the resulting terrestrial planets. The AMD of a planet is the difference between its orbital angular momentum and the orbital angular momentum of a planet of identical mass and semimajor axis in a circular orbit with zero inclination (e.g., Laskar 1997). We use the terrestrial planets' AMD to compare the resulting post-collision/merger system to the terrestrial planets in our Solar System. Additionally, we calculate several parameters of the collision, which allow us to determine the internal properties of the impact-produced subsystem. By internal properties, we are referring to the magnitude of the angular momentum of the Earth-Moon system around its center of mass and the obliquity of the system relative to the plane of its orbit about the Sun. Our results will be made available for use as input for hydrodynamic simulations of the actual Moon-forming impact event being performed by other research groups.

We have performed a series of N-body integrations in which the mass ratio of the Earth-Moon progenitors is 8:1, 4:1, or 1:1. Although most of our simulations result in a collision, in the majority of the runs the wrong bodies collide or the Earth-Moon progenitors collide too quickly after the start of a simulation. Some runs last 200 Myr without a collision or ejection. Nonetheless, there are some simulations in which the Earth-Moon progenitors do collide 8 - 200 Myr after the runs start; a few of these have terrestrial planet AMD values similar to that of the inner Solar System. Note that this diversity of outcomes is expected from such configurations, and it implies that the particular configuration of the Solar System is the consequence of stochastic processes, which should lead to a variety of planetary systems about other stars. Various aspects of our results have been presented at the following meetings: Protostars and Planets IV, Origin of the Earth-Moon System, American Geophysical Union, Division of Planetary Sciences/AAS, Division on Dynamical Astronomy/AAS (1999 and 2000). This research was described in detail in Eugenio Rivera's Ph. D. thesis, which was filed in January of 2002. We are currently writing our results up for publication.

ii) Dynamical Connections between Giant and Terrestrial Planets

In our Solar System, the dynamics of the terrestrial planets and the giant planets are not strongly coupled to each other, at least in the sense that secular perturbations are able to transport angular momentum deficit (AMD) far more efficiently among the terrestrial planets and among the giant planets than between the two subsystems (Laskar 1997). This is indeed fortunate, because the giant planets have about one thousand times as much AMD as would be required for the terrestrial planets to become orbit-crossing.

We have performed several simulations designed to see whether the formation of a terrestrial-mass planet in the asteroid belt would have affected the dynamical evolution of the inner Solar System by coupling it more efficiently with the giant planets. The systems which we have simulated consist of the Solar System planets and a planetary-sized (0.1 - 10 Earth masses) "asteroid" in the asteroid belt. An integration with Ceres at 5 Earth-masses remained stable for a billion years. Runs with Hygiea at 5 Earth masses and with Vesta at 2 Earth masses also remained stable for the entire 100 million years that we simulated. Thus, a moderate mass planet in the asteroid belt would not necessarily destabilize the orbits of the terrestrial planets, i.e., the presence of a gap between the giant planets and the terrestrial planets does not seem to be a requirement for planetary habitability.

Runs with Ceres at ten Earth masses, however, caused the system to become unstable at ~ 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 systems to become unstable in less than 100 million years. These results were published in Icarus (Lissauer et al. 2001).

iii) Dynamics of the Upsilon Andromedae Planetary System

We have done many numerical orbital integrations designed to test the stability of the three planets detected in orbit around the star upsilon Andromedae and possible smaller bodies orbiting in the system which have not yet been discovered. We used planetary orbital parameters derived using observations through early to mid-2000. These new fits result in significantly more stable systems than did the initially announced planetary parameters. Our results were published in the Astrophysical Journal (Lissauer and Rivera 2001).

iv) Dynamics of the Planets Orbiting GJ 876

We performed two planet Newtonian fits to radial velocity measurements of GJ 876. Our fits provided much better fits to the data than do Keplerian fits. Most sets of planetary parameters that we derived are stable for at least 100 million years (Rivera and Lissauer 2001).

iv) Integrators for Planetary Accretion in Binaries

We derive and test two new symplectic integrator algorithms, suitable for studying planetary accretion in binary star systems. One algorithm follows planets orbiting a single star, perturbed by a distant companion; the other follows planets that orbit both binary members (Chambers et al. 2002).

References:

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