THE ROLE OF GIANT PLANETS IN TERRESTRIAL PLANET FORMATION. H. F. Levison, *Department of Space Studies, Southwest Research Institute, Boulder CO 80302 (hal@gort.boulder.swri.edu)*, L. Dones, C. Agnor, R. Canup, *Department of Space Studies, Southwest Research Institute, Boulder CO 80302*, M.J. Duncan, *Department of Physics, Queen's University, Kingston, Ontario, Canada K7L 3N6*.

The dynamical structure of the giant planets has played an important role in determining the sizes, numbers, and general habitability of the terrestrial planets. For example, the presence of Jupiter has been shown to affect the formation of terrestrial planets in the Solar System [1]. Here we present a progress report of a continuing study of the coupling between outer planetary system architecture and inner planetary system formation. The specific goal of this project is to determine the sensitivity of terrestrial planet formation to outer planetary system architecture, and to thereby gain a quantitative handle on one key factor in determining the types of planetary systems in which rocky inner planets might be able to support stable biosystems.

The first step of the program was to perform a set of bottom-up numerical simulations designed to generate plausible giant planet systems from a large number of planetary embryos [2]. Our simulations produced systems that are stable for at least for a billion years and which exhibit a wide range of characteristics. Some of these systems are reminiscent of the outer Solar System. The number of giant planets ranged from one to seven. Many systems contained only Uranus-mass objects. We constructed systems that were more compact than the outer Solar System as well as systems that were much sparser, with planets on very eccentric orbits.

The second step of this program is to construct terrestrial planets in our synthetic outer planetary systems. We report on this effort here. In particular, we are studying the growth of terrestrial planets in 4 different outer planetary systems: $i)$ the Solar System's outer planets, $ii)$ a system with larger planets than the Solar System, $iii)$ a system with 7 Uranus-mass planets, and $iv)$ a system with three Saturn-mass objects on eccentric orbits. The last three systems are taken from our synthetic giant planet systems [2] and are illustrated in Figure 1. For each of these systems, we usually performed 4 runs in order to start to develop a statistical understanding of the role that giant planets play in terrestrial planet formation.

Initially, each run consists of the Sun, giant planets, and 100 planetary embryos. The embryos initially had semi-major axes between 0.5 and 3 AU and were distributed so that the surface density of the population fell as $r^{-1.5}$. Our choice of the inner edge of the population was set to make the problem tractable since it determines the timestep of the integration. Each embryo had an initial mass of $0.04\,M_{\oplus}$ making a total mass in the terrestrial zone of $4\,M_{\oplus}$. The initial eccentricities of the embryos were chosen from a uniform distribution between 0 and 0.02, and inclinations were set to $e/2$. Their initial longitude of perihelion, the longitude of the ascending node and the mean anomaly were chosen randomly from a uniform distribution between 0 and 2π.

The orbits of the embryos were integrated by using a full N-body, symplectic algorithm known as SyMBA [3,4]. The integration was done using a timestep of 0.015 years and lasted a total of 2×10^8 years. During the integration, if two objects came to within a distance equal to the sum of their physical radii, they were assumed to merge into a single object in which mass and linear momentum was conserved.

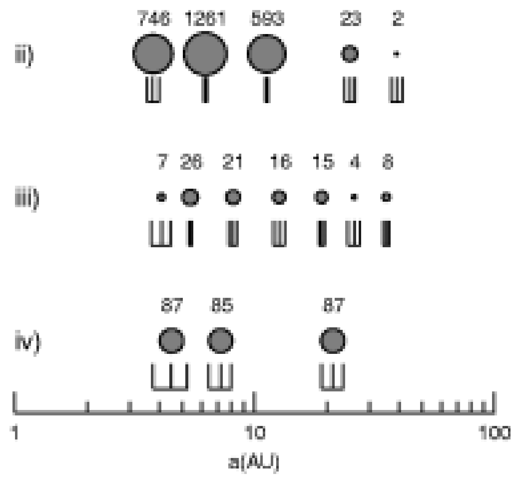

Figure 1 — The three synthetic outer planetary systems we employ in these simulations. Positions of a circle along the abscissa indicates the planet's semi-major axis. The size of the circle indicates the planetary mass. In addition, the mass of the planet, in Earth masses, is printed above each planet. The markings beneath each planet indicate the range of distances from the planet's sun (periastron and apastron) with the central vertical line indicating the semi-major axis.

Figure 2 shows the results of the four simulations done under the influence of the giant planets in the Solar System. This can be compared with Figure 3 which shows the real terrestrial planets in the same manner. The agreement is quite good. Our simulations usually produce 2 large terrestrial planets at roughly the correct locations and with roughly the correct masses. However, the eccentricities of the planets are larger than those observed for the terrestrial planets in the Solar System. This result is consistent with previous attempts at the same problem [5,6]. It is not clear why these eccentricity differences occur and thus this is an area of active research.

Very little accretion occurs outside of $\sim 1.5\ AU$. In our simulations, embryos in this region are initially excited to large eccentricities. This is due to a combination of strong mean motion resonances and the ν_6 secular resonance located in this region. Then they are either removed from the terrestrial region due to close encounters with the giant planets, or they are accreted by the larger terrestrial embryos closer to the Sun (also see [7]).

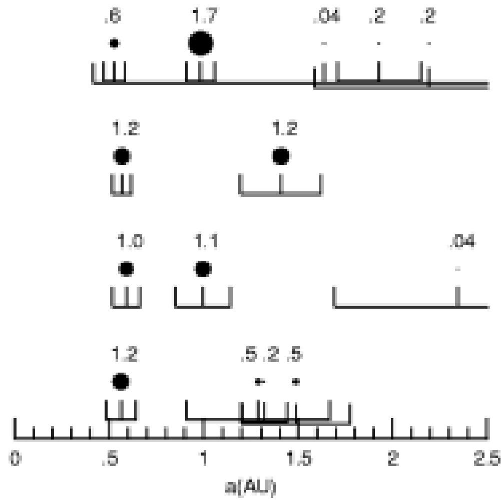

Figure 2 — Similar to Figure 1 but for the 4 synthetic terrestrial planetary systems that formed under the influence of the giant planets in the Solar System.

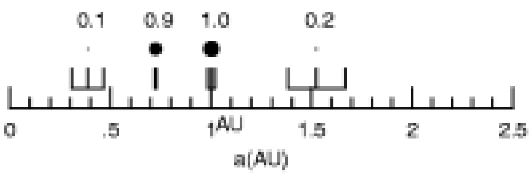

Figure 3 — Similar to Figure 1 but for the terrestrial planets in the Solar System.

The terrestrial planets that formed under the influence of the giant planet system with more massive planets than our own (Figure $1ii$) show two distinct differences from those in Figure 2. First, there are no large terrestrial planets outside of $1\ AU$. Second, the largest terrestrial planets in these runs are typically larger than those that formed under the influence of planets in the Solar System. This is due to the fact that the embryos beyond $1\ AU$ evolved onto large eccentricity orbits and were accreted by the growing planets interior to $1\ AU$.

The terrestrial planet systems that formed under the influence of the giant planet system with 7 small giant planets (Figure $1iii$) are remarkably similar to those shown in Figure 2. The only difference is that planets interior to $1\ AU$ are slightly larger. This is due to the fact that the eccentricities of the embryos near $1\ AU$ are slightly larger in these runs, which feeds material inward to the planets growing interior to $1\ AU$.

Finally, Figure 4 shows the results of the three simulations done under the influence of the giant planet system with 3 Saturn-mass giant planets on eccentric orbits (in Figure $1iv$). These systems are significantly different from those that formed in the other outer planetary systems in that very little accretion occurred outside of $\sim 0.6\ AU$.

In these simulations we find an interesting correlation between the locations of large terrestrial planets and the *eccentricity* of the innermost giant planet (Figure 5). The reason for this is not yet clear and is the focus of ongoing research. It should be noted that there is no obvious correlation between the location of terrestrial planets and the mass of the giant planet system.

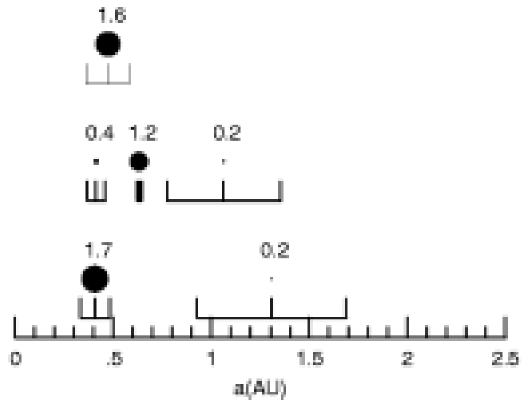

Figure 4 — Similar to Figure 1 but for the synthetic terrestrial planetary systems that formed under the influence of the giant planets in Figure $1iv$.

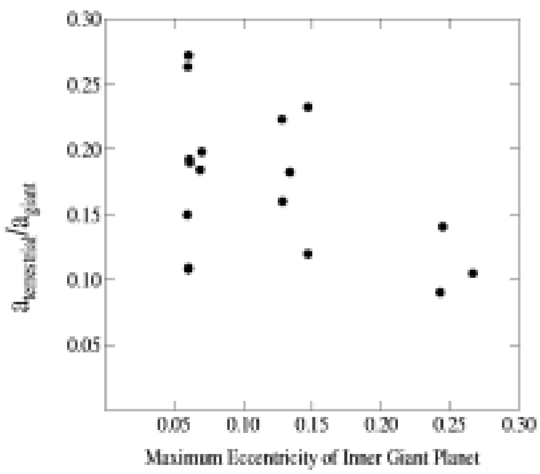

Figure 5 — The ratio of a terrestrial planet's semi-major axes to that of the innermost giant planet as a function of the largest eccentricity of the innermost giant planet. Only terrestrial planets larger than $1\ M_\oplus$ are plotted.

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References: [1] Wetherill, G.W. 1996. *Icarus*, **119**, 219. [2] Levison, H.F., Lissauer, J.J., & Duncan, M.J. 1998. *Astron. J.*, **116**, 1998. [3] Duncan, M., Levison, H, & Lee M.H. 1998. *Astron. J.*, **116**, 2067. [4] Levison, H.F. & Duncan, M.J. 2000. *Astron. J.*, **120**, 2117. [5] Chambers, J. & Wetherill, G.W. 1998. *Icarus*, **136**, 304. [6] Agnor, C.B., Canup, R.M., & Levison, H. F. 1999. *Icarus*, **142**, 219. [7] Morbidelli, A., Chambers, J., Lunine, J. I., Petit, J. M., Robert, F., Valsecchi, G. B., & Cyr, K. E. 2000. *Meteoritics & Planetary Sci.* **35**, 1309.