SIMULATIONS OF TERRESTRIAL PLANET FORMATION WITH STRONG DYNAMICAL FRICTION: IMPLICATIONS FOR THE ORIGIN OF THE EARTH'S WATER. D. P. O'Brien[1,2] (obrien@psi.edu), A. Morbidelli[2], and H. F. Levison[3], [1]*Observatoire de Nice, B. P. 4229, 06304 Nice Cedex 4, France,* [2]*Planetary Science Institute, 1700 E. Ft. Lowell Rd., Suite 106, Tucson, AZ 85719,* [3]*Department of Space Studies, Southwest Research Institute, 1050 Walnut St., Suite 400, Boulder, CO 80302*.

Overview: We have performed 8 numerical simulations of the final stages of accretion of the terrestrial planets, each starting with over 5× more gravitationally interacting bodies than in any previous simulations. Given the large number of small planetesimals in our simulations, we are able to more accurately treat the effects of *dynamical friction* during the accretion process. Dynamical friction is the equipartition of energy between large and small bodies in a population, resulting in the damping of relative velocities amongst the large bodies. We studied the effects of the orbits of Jupiter and Saturn on the final planetary systems by running 4 of our simulations with the present, eccentric orbits of Jupiter and Saturn (the EJS simulations) and the other 4 using a nearly circular and co-planar Jupiter and Saturn as predicted in recent models of the evolution of the outer Solar System [1,2,3] (the CJS simulations). We find that the final planets formed in our CJS simulations are much more geochemically consistent with the Earth, primarily in terms of the presence of significant amounts of water as well as in the abundance of siderophile elements in their mantles.

Method: For our simulations, we use SyMBA [4], which is a symplectic N-body integrator that handles close encounters and the merging of bodies. SyMBA allows for a population of gravitationally interacting massive bodies as well as a population of less-massive bodies that interact with the massive bodies but not with one another. Hence, it is an ideal tool for modeling the final stage of terrestrial planet accretion, in which there is a population of massive embryos and a much more numerous population of less-massive planetesimals.

For the initial distribution of planetary embryos and planetesimals in our simulations, we use a distribution based on that of [5] (their simulations 21-24) and extended to 4 AU, with planetesimals 1/40 as massive as the embryos. Our initial distribution contains 25 roughly Mars-mass embryos and an equal mass of material in a population of ∼1000 planetesimals. A timestep of 7 days is used in all of our simulations, and all simulations are carried out for 250 Myr. 4 simulations are performed with a circular and co-planar Jupiter and Saturn (CJS), and 4 are performed with Jupiter and Saturn on their present, eccentric and inclined orbits (EJS).

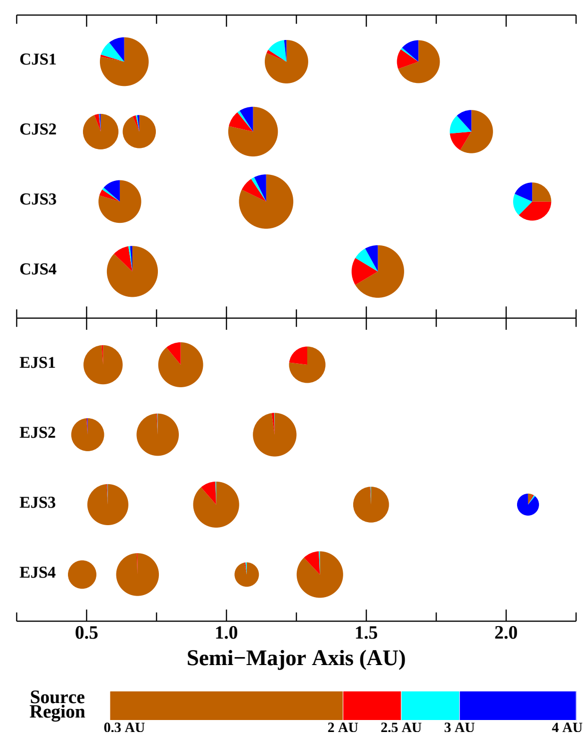

Figure 1: Final terrestrial planets formed in all of our simulations. Pie-diagrams show the relative contribution of material from the different semi-major-axis regions, and the diameter of each symbol is proportional to the diameter of the planet.

Final Planetary Systems: In each of our simulations, a stable system of terrestrial planets is formed within 250 Myr. The resulting systems are shown in Fig. 1. The planetary systems formed in the EJS simulations have, on average, a larger number of less-massive planets than in the CJS simulations, and the center of mass of those systems is closer to the Sun than in the CJS simulations.

In those respects, the EJS simulations are a closer match to the actual Solar System. However, it is possible that future simulations incorporating even more dynamical friction (eg. higher numerical resolution) could eliminate this discrepancy between the CJS simulations and the actual Solar System.

Water: As shown in Fig. 1, planets in the CJS simulation consist of much more material from beyond 2.5 AU than those in the EJS simulations. Material from beyond 2.5 AU is a likely source of water and other volatiles (eg. carbonaceous chondrite meteorites can contain up to 10% water by mass and have oxygen isotope ratios comparable to that of the Earth [6,7,8,9]). In our CJS simulations the fraction of each planet's total mass that originates from beyond 2.5 AU has a median value of 15%, while in the EJS simulations it is 0.3%. The delivery of material from beyond 2.5 AU generally occurs late in a planet's growth, and in the case of embryos, often as the final large impact. In the CJS simulations, the median relative mass fraction of material originating from beyond 2.5 AU that is delivered by embryos is 76%, while none of the planets in the EJS set of simulations experiences an impact of an embryo from beyond 2.5 AU (there is one planet that is essentially just an embryo that originated from beyond 2.5 AU). The lack of material from beyond 2.5 AU in the EJS simulations is due to the rapid clearing of the outer asteroid belt, which is stronger in our simulations than in previous simulations with lower numerical resolution [8,9].

Even with conservative values for the water content of material from beyond 2.5 AU and for the fraction of water retained in impacts, most planets in the CJS simulations would contain several Earth-oceans of water, while for even the most optimistic values, the majority of the planets in the EJS simulations would not contain enough water to be Earth-like. Hence, having an initially circular Jupiter and Saturn is more consistent with the Earth's water being delivered mainly through material from the outer asteroid belt. Note that in the model of [1,2,3], even though Jupiter and Saturn are initially circular and co-planar, they eventually cross their 2:1 mean-motion resonance and evolve to their present orbits, such that the CJS initial conditions are not inconsistent with the current state of the Solar System.

Siderophile Abundances: It was suggested in [10] that having the Earth's water originate from the outer asteroid belt would result in an excess of siderophile elements in the Earth's mantle. However, this assumes that the water is delivered in a *late veneer* after differentiation has ceased. In our CJS simulations, nearly all water is delivered through impacts up to and including the final impact by a large embryo, such that it can be reasonably assumed that most siderophile elements delivered to the planets in those impacts would be segregated into their cores. Only about 1% of the total mass of the planets is accreted after the last giant impact (and hence after differentiation has likely stopped), comparable to the estimate of [10] for the maximum amount of material in the late veneer that would be consistent with siderophile abundances in the Earth's mantle. In contrast, nearly 10% by mass, on average, is delivered to the planets after the last giant impact in the EJS simulations, such that those planets would have siderophile abundances in their mantles that are much higher than that of the Earth.

Summary: With high-resolution numerical simulations of terrestrial planet accretion, we find that an initially low-eccentricity and inclination Jupiter and Saturn, as predicted in the model of [1,2,3], is consistent with the delivery of water to the Earth from outer-asteroid-belt material as well as the abundance of siderophile elements in the Earth's mantle. If Jupiter and Saturn began on their present eccentric and inclined orbits, the terrestrial planets would accrete very little water-bearing material from the outer asteroid belt, necessitating another source of water, eg. [10,11,12]. Even then, it is likely that the resulting planets would have siderophile abundances in their mantles that are much larger than that of the Earth.

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