ASTEROIDAL SOURCES OF EARTH'S WATER BASED ON DYNAMICAL SIMULATIONS. J. Lunine[1], A. Graps[2,3], D.P. O'Brien[3], A. Morbidelli[4], L. Leshin[5], A. Coradini[2]. [1]Lunar and Planetary Laboratory, Univ. of Arizona, Tucson, AZ 85721, jlunine@lpl.arizona.edu, [2]Istituto di Fisica dello Spazio Interplanetario (INAF), Rome, Italy, [3]Planetary Science Institute, Tucson AZ, [4]Obs. Côte d'Azur, Nice, France, [5]NASA Goddard Spaceflight Center, Greenbelt MD.

Introduction: Water defines the Earth: it is the working fluid of meteorology, erosion and carbon dioxide scrubbing from the air, the dominant contributor to the radiative balance of the atmosphere, the principle surface cover of our planet (as ocean and cloud), an important agent in crustal tectonic processes, and the fundamental liquid medium for life [1,2]. The origin of Earth's water—that is, which putative early solar system reservoirs were important source regions —and its sensitivity to initial conditions of terrestrial planet formation are therefore interesting scientific issues. Here we present the implications for these problems of new and recent dynamical simulations.

Potential reservoirs: In this study we divide the inner solar system during terrestrial planet formation into five different regions defined by the water abundance of the embryos formed within each. Inward of 1.5 AU, we assume the planetesimals were dry; that is, they possessed a water abundance--expressed as mass fraction relative to the bulk composition--below 10^{-4}. (The actual value is arbitrary so long as it is below that required to supply in the minimum known abundance of the Earth's water). Nebular models predict temperatures at 1 AU, at a time when most solid material was in the form of tiny grains, too high for silicates to incorporate a significant amount of water. Had the disk temperature profile been such as to allow ice condensation or even hydration of silicates at 1 AU [3], we might also expect to find a carbonaceous chondritic composition for planetesimals in the 1 AU region, and for the Earth itself. However, the Earth cannot be mostly carbonaceous chondritic [4]. It is possible that some water was adsorbed from the gas directly onto grains at 1 AU [5], but it is not known whether this could have been a major contributor.

It is possible to array the chondritic meteorite classes according to their water abundance [6] and distance from the Sun at which their parent bodies may have resided. This is done in figure 1. There are uncertainties here both in regard to the birth regions of the parent bodies and in the water abundances of the ordinary and enstatite chondrites in particular. There is the more fundamental question of whether the meteorite classes available for study represent the range of primitive material and planetary embryos present in the inner solar system at the time of planet formation, and whether water abundance in planetary embryos was in fact correlated with other properties (oxygen isotope ratios in the silicates, siderophile element distribution) in the way seen in the chondritic meteorite samples collected for study.

We propose two additional planet-building materials in figure 1 not represented by the known meteorite classes. One, labeled "dry", is the water-poor material in the 0.3-1.5 AU region from which the bulk of the Earth, and perhaps Mars, were formed, with geochemical signatures compatible with those seen in the Earth [4]. The second putative material "MB Comet" is a carbonaceous chondritic rock with ~ several to ten times the amount of water relative to what is measured in carbonaceous chondritic meteorites. This additional water was present as ice. Both the inference that chondrites were hydrated through the presence of ice in the asteroid belt and the discovery of several comets that are inferred to have their point of origin in the outer part of the main belt [7] motivate the introduction of this class of bodies at and beyond 3 AU. In figure 1 we assign color codes to the resulting five classes of planetary embryos and their smaller debris, which are then used to parse the amount of material gained by the terrestrial planets from each of the various reservoirs.

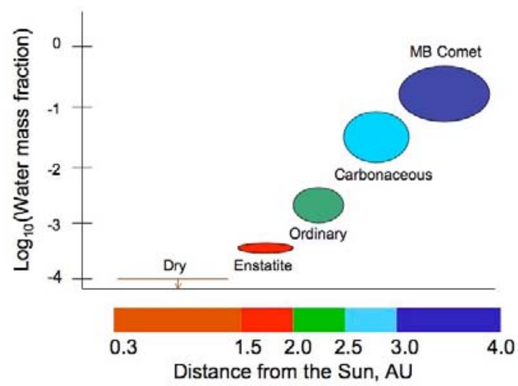

Fig. 1. Assumed water abundances in planetary embryos as a function of heliocentric distance in astronomical units. The color coding associated with the different reservoirs and associated water abundances is carried over to figure 2.

Dynamical simulations: The simulations we report are a superset of those published recently by [8]. The "circular Jupiter Saturn" (CJS) simulations start with Jupiter and Saturn on nearly circular and co-planar orbits as suggested by the "Nice Model" [10] (with semi-major axes of 5.45 AU and 8.18 AU respectively), and the EJS simulations start with Jupiter and Saturn on their current eccentric orbits. In the EJS simulations, the eccentricities of Jupiter and Saturn decay to near-zero values on a timescale of roughly 50 Myr due to the ejection of material from the system. We have run a new set of models the preliminary results of which we are reporting here. These “ECJS” models have Jupiter and Saturn in their current eccentricities and inclinations, but with initial *a* values predicted by the Nice Model [10].

Results: The results of twelve simulations are shown in figure 2. The total amount of water the Earth must have accreted to explain the present day surface, crustal and (very uncertain) mantle water is ~10^{-3} the total mass of the Earth, a generous value that allows for a factor of two loss of water during collisions of the large embryos with the growing Earth [9]. In terms of the fraction of the Earth’s mass that must be acquired from material beyond 1.5 AU, this corresponds to 10-100% ordinary chondritic material, 1-10% carbonaceous chondritic material, or 0.1-1% MB Comet (ice-bearing carbonaceous chondritic) material. The CJS models deliver relatively more water from the MB Comet region than do the other two classes of models, while the EJS delivers water almost exclusively from the ordinary and enstatite reservoirs. The ECJS cases are intermediate in this regard, having a significant contribution from the carbonaceous and ordinary chondrites but less from enstatites and the MB Comets.

From the point of view of the solar system’s dynamical history [10], the CJS and ECJS models are preferred. However, they deliver to the Earth more carbonaceous chondritic material than the one-to-several percent imposed by the mantle’s siderophile element abundance and disparity in oxygen isotope values for carbonaceous chondrites relative to the Earth and Moon [4]. If the carbonaceous embryo that delivered the water were differentiated, then its core, containing most of the siderophile elements, would not mix with the Earth’s mantle. This seems reasonable to us and in line with Hf-W chronology constraints [1]. The oxygen isotopic constraint might be lessened if the isotopic compositions of the Earth and the Moon were homogenized soon after the giant impact that formed the latter [11]. More work must be done to evaluate this possibilities as well as the implications of early delivery of a water rich embryo before or during terrestrial core formation. But our present results emphasize and extend the conclusion of previous work, that addition of material from large bodies beyond the orbit of Mars occurred extensively throughout the time of the Earth’s growth, and likely contributed substantial amounts of water to our home world.

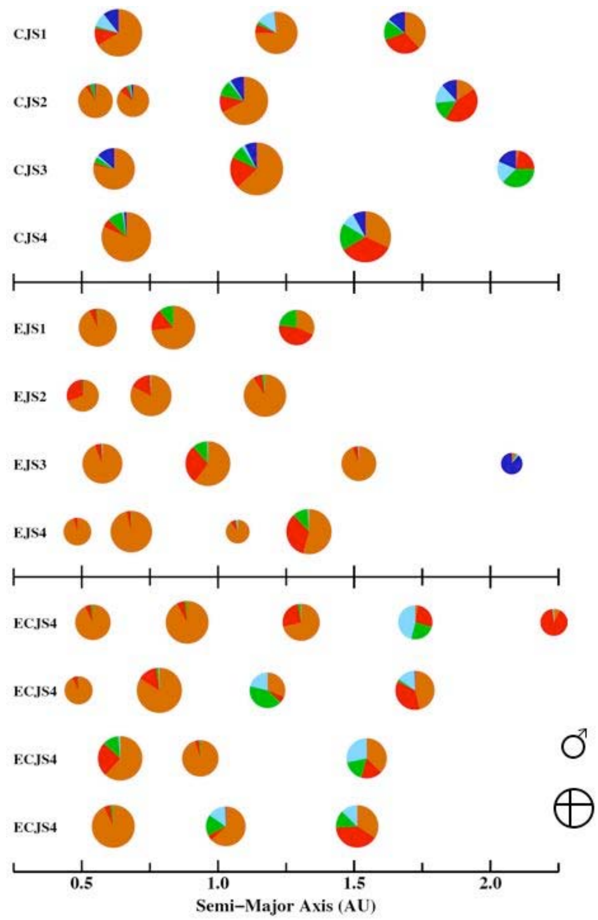

Fig. 2. Results of three sets of dynamical simulations showing the fraction of material derived from various regions of the inner solar system for bodies grown under different assumptions about the initial conditions of the giant planets (not shown). Diameter of each circle is proportional to the planet diameter; the sizes of Earth and Mars are shown on the right for comparison.

References: [1] Halliday, A. (2004) in *Treatise on Geochemistry* v. 1, pp. 509-557, Elsevier, Amsterdam. [2] Abe, Y et al. (2000) in *Origin of the Earth and Moon,* pp. 413-433. Tucson, U Arizona. [3] Podolak , M. and Zucker (2004). *M&PS* 39, 1859-1868. [4] Drake, M. and Righter, K. (2002). *Nature* 416, 39-44. [5] Sitmpfl. M. et al. (2004) *M&PS* 39 Abst #A99. [6] Wood, J. (2005) in *Chondrites and the Protoplanetary Disk* ASP v. 341, 955-973. [7] Hsieh, H, and Jewitt, D. (2006). *Science* 312, 561-563. [8] O’Brien D. et al. 2006. *Icarus* 184, 39-58. [9] Canup, R. and Pierazzo, E. (2006). *LPSC XXXVII*, Abstr.# 2146. [10] Gomes, R. et al. (2005) *Nature* 435, 466-469. [11] Pahlevan, K., Stevenson, D.J. *BAAS* 38, Abst # 66.03.