THE COMPOSITION OF SIMULATED TERRESTRIAL PLANETS. J. C. Bond[1], D. S. Lauretta[1] and D. P. O'Brien[2], [1]Lunar and Planetary Laboratory, University of Arizona, Tucson AZ 85721. jbond@lpl.arizona.edu, [2]Planetary Science Institute, Tucson AZ 85719.

Introduction: The origin of the bulk compositions and dynamical states of the terrestrial planets is still not completely understood. Few studies have been performed to explore these two constraints by combining detailed dynamical and chemical studies together to obtain a more coherent planetary formation model. For example, many dynamical terrestrial planet formation studies have determined an approximate range of how much water was added to the resulting planets (e.g. [1], [2]) or considered possible material for the late veneer ([2]). However, no dynamical studies have undertaken a detailed examination of the bulk chemical composition of the resulting planets as a test of their simulations. Such a study is essential in determining how well these numerical simulations can constrain the formation of the terrestrial planets. Furthermore, such studies are key in determining the chemical nature of possible extrasolar terrestrial planets. Here we present the results of our ongoing study to combine N-body dynamical simulations with equilibrium condensation models in protoplanetary disks.

Methodology: We constrain the bulk chemistry and elemental distribution of our system by assuming that each planetary embryo and planetesimal in our dynamical simulations retains the equilibrium chemical composition of the area of the nebula in which it first formed, and contributes that composition to the final planet. As such, by tracing the origin of each embryo and planetesimal in our dynamical simulations, and calculating the chemical composition of those bodies based on their original locations, we are able to constrain the bulk composition of the final terrestrial planets based on the composition of the bodies that combine together to form them.

Dynamical Models. The high-resolution N-body simulations of terrestrial planet formation in our Solar System utilized by this work are taken from [2]. These simulations extend the work of [3] and incorporate the effects of dynamical friction on the accretion process to produce planetary systems that dynamically resemble our own. The output from one such simulation can be seen in Figure 1. Each simulation consisted of ~25 Mars-mass planetary embryos and ~1000 planetesimals (with a total mass equal to the total mass of the embryos) that initially span the region from 0.3 to 4 AU. Four of the simulations were run assuming the current orbits of Jupiter and Saturn (EJS), and four were run with the initially circular, low-inclination Jupiter and Saturn predicted by the *Nice Model* [4] (CJS).

Chemical Models. The equilibrium composition of solids condensed in the nebula, and hence the initial compositions of the planetesimals and embryos, was determined by using the commercially available HSC Chemistry (v. 5.1) software package. Simulations were run with 16 different elements (H, He, C, N, O, Na, Mg, Al, Si, P, S, Ca, Ti, Cr, Fe and Ni) at solar abundances as taken from [5]. Pressure and temperature conditions in the disc were adopted from [6] at 7 different times ($2.5x10^5$ yr, $5.0x10^5$ yr, $1.0x10^6$ yr, $1.5x10^6$ yr, $2.0x10^6$ yr, $2.5x10^6$ yr, $3.0x10^6$ yr). Compositions and the condensation sequence produced are in agreement with previous studies (e.g. [7])

Results: We find that the compositions of all of the simulated planets from [2] are in reasonable agreement with the current range of estimates of bulk planetary abundances for Venus [8], Earth [8] and Mars [9]. However, those produced using the disk conditions at $5x10^5$ yrs are the best match. Using these conditions, all values are correct to within 1 wt% except for Mg, O, S and Si (EJS only). Mg values are low by up to 5 wt%, O is high by up to 4 wt%, S is high by up to 4 wt%, and Si is high by up to 2 wt% (EJS only). An example of the elemental planetary composition produced for the central planet (analogous to Earth) in the same example simulation as previously shown in Figure 1 can be seen in Figure 2.

The composition of each simulated planet from [2] is normalized to that of its analogous planet. For example, the inner most planet is normalized to the composition of Venus. The simulated abundances are in good agreement except for the volatile elements S and Na (Figure 3). These enrichments suggest that outward migration of volatile elements and species may have redistributed material in the early Solar System. Water is hypothesized to migrate outwards as the disk evolves and it is reasonable to assume that other volatile species (such as Na) would exhibit the same trend. Future models will consider such migration to determine if this effect can reconcile the observed Na spike.

We also differ from the planets of the Solar System in our Mg/Si ratios, which range from 0.47 to 0.76 and are all below current planetary levels. While the exact cause of this difference is still unknown, it does imply that there is some other way to fractionate one or both

of these elements in the early Solar System that is not captured in the current chemical models.

Extrasolar Planetary Systems: As many of the currently known extrasolar planetary host stars are chemically unusual, the compositions of their companion planets is also expected to be unusual. Several host stars have C/O ratios close to 1 and have Mg/Si ratios ranging from 0.7 to 2.6. These variations have the potential to drastically impact the composition of any terrestrial planets present within the system. Simulations to address these possible effects are currently underway.

Conclusions: We have found that detailed chemical and dynamical models can be successfully combined together to produce elemental abundances of the terrestrial planets that are in good agreement with the actual planets being modeled. This method is not complete but the success of our initial studies implies that it can be applied successfully to other simulations and systems, such as known extrasolar planetary systems.

References: [1] Raymond S. N. et al. (2004) *Icarus*, *168*, 1. [2] O'Brien D. P. et al. (2006) *Icarus*, *184*, 39. [3] Chambers, J. E. (2001) *Icarus*, *152*, 205 [4] Gomes F. et al. (2005) *Nature*, *435*, 466. [5] Asplund et al. (2005) *ASPC*, *336*, 25A. [6] Hersant F. et al. (2001) *ApJ*, *554*, 391. [7] Pasek, M. A. et al. (2005) *Icarus*, *175*, 1. [8] Morgan, J. W. & Anders, E. (1980) *Proc. Natl. Acad. Sci. 77*, 6973. [9] Lodders, K. & Fegley, B. (1997) *Icarus*, *126*, 373.

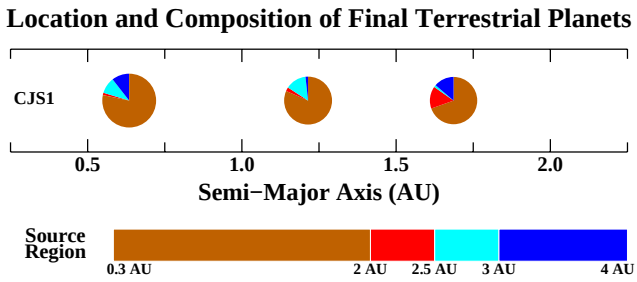

Figure 1: Final terrestrial planets formed in the CJS1 simulation of [1]. Pie diagrams show the contributions of material from the different semi-major-axis regions, and the diameter of each symbol is proportional to the diameter of the planet.

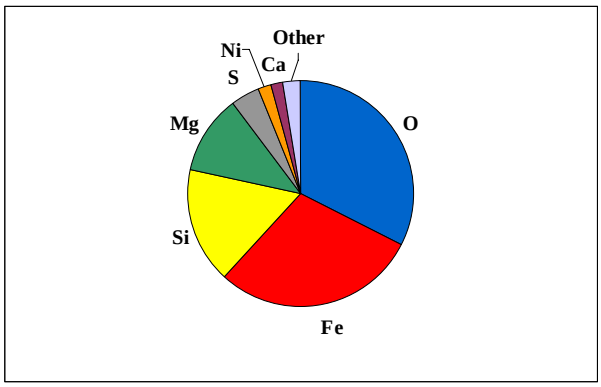

Figure 2: Diagram of the bulk composition of the central simulated planet from the [2] CJS1 simulation. This planet is taken to be analogous to Earth, based on its orbital parameters ($M = 0.81M_{Earth}$, $R = 1.214$AU).

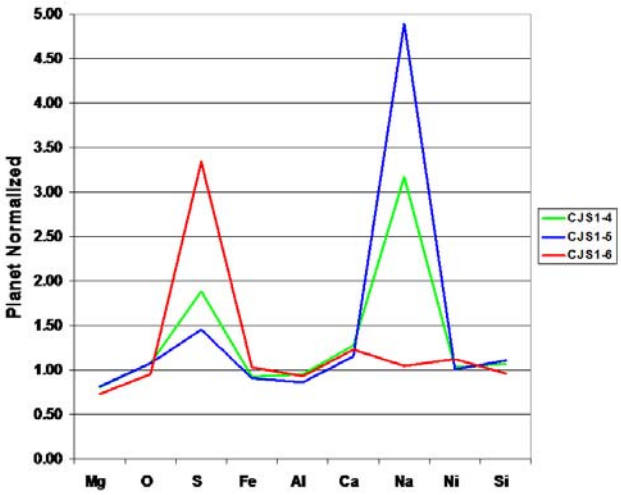

Figure 3: Spider plot of the planet normalized compositions of the same three planets from Fig. 1. The green line is for the Venus-normalized inner planet, blue is for the Earth normalized middle planet and red is for the Mars normalized outer planet.