TESTING ACCRETION MODELS AGAINST THE "PEAS IN A POD" OBSERVATION OF EXOPLANETS. J. L. Noviello[1], S. J. Desch[1], A. P. Jackson[1]. [1]School of Earth and Space Exploration, Arizona State University, Tempe, AZ, USA, 85287. Jessica.Noviello@ASU.edu.

Introduction: Exoplanets have been found in myriad sizes and periodicities orbiting hundreds of stars, but there is evidence that these characteristics are well-ordered within exoplanet systems. Weiss et al. [1] found strong evidence in the California-*Kepler* Survey (CKS) dataset that the planets within each multi-planet system are relatively equal in size and orbital spacing, a finding they call the "peas in a pod" model [1]. A series of bootstrap analyses that created and analyzed synthetic radius and period ratios of randomly selected planets did not recover the observed correlations between masses or periods of neighboring planets. They interpreted this result to support *in situ* formation of planets via runaway growth, specifically that the multi-planet systems in the CKS dataset have masses that reflect densities in the disk, and are not attributable to stochastic growth by hierarchical accretion; and that the period spacings reflect formation conditions in the disk, and have not been affected by significant differential migration or orbital scattering [1].

These conclusions, that the masses and periods of CKS planets reflect formation in the disk, appears more consistent with growth by pebble accretion than hierarchical growth. Traditional models [2,3,7] assume growth by pairwise collisions between small bodies. Due to the stochastic nature of hierarchical growth, no strong correlations are expected between masses or orbital spacings of neighboring planets. In pebble accretion models [4-5], planetesimals grow to planet-sizes within a few Myr, thanks to a combination of gravitational focusing and aerodynamic drag of small (< meter-sized) particles accreted directly from the disk. As planets accrete directly from the disk in pebble accretion models, it is hypothesized that they would yield the best match to the peas-in-a-pod observation [1].

We test various formation models to see if they reproduce the peas-in-a-pod pattern. Recovering the patterns detailed in [1] could help validate or rule out formation models and motivate future work in a particular direction. As a baseline before including pebble accretion, we first consider the case of purely hierarchical growth.

Data and Methods: We examine a set of 60 N-body simulations run with the Mercury N-body code [6]. All simulations begin initially with 15 embryos of 0.15 Earth mass and 150 planetesimals of 0.015 Earth mass for a total of 4.5 Earth masses of material initially. The embryos and planetesimals are distributed between 0.4 and 4 AU from a 1 solar mass star. In addition a Jupiter-mass planet is placed at 5.2 AU. The simulations were run for 100 Myr. In half of the simulations the bodies are spaced evenly while in the other half the semi-major axis is chosen randomly. We find no difference between the two sets of initial conditions. Note that while these initial conditions are known not to perfectly reproduce the Solar system (producing a Mars analogue that is significantly too large) the goal here is not to reproduce the Solar system but to produce a roughly analogous system of terrestrial planets.

Each of the 60 iterations of the N-body simulation produced at least two planets in addition to the Jupiter-mass planet, which we did not include in subsequent analyses. In total the simulations produced 199 planets which translated into 139 pairs of planets.

Comparative calculations: The output of these 60 iterations included the orbital semi-major axes of these planets and the masses of these planets in units of solar mass. The masses were converted into Earth masses, which were then used to calculate approximate planet radius using three different parameterizations [8, 9]. This enables direct comparison to the observations in [1]. We note that the CKS survey is reasonably complete down to radii of 0.4 Earth radii. We then graphed different attributes of planet pairs, where the inner planet is P_1 and the outer planet in the pair is P_2 and continued until no more planets in the system remained. For each iteration with M planets, $M–1$ planet pairs were calculated.

Next, we performed linear regressions on the following planet attributes: 1) The mass of P_1 against the mass of P_2; 2) The period ratios of P_3/P_2 against P_2/P_1; 3) The log vs. log of the mass ratios P_3/P_2 and P_2/P_1; and 4) The log vs. log of the period ratios P_3/P_2 and P_2/P_1. Here planet 1 could be any of M-2 planets, and planets 2 and 3 are the next two planets farther out. In items 3 and 4, the linear slope is interpreted as an exponent in a power law equation.

Finally, we report the full equation of the linear model and the goodness-of-fit of the linear model to the data as r^2. We also include a p-value of the Pearson r^2 coefficient, with a significance level of $\alpha = 0.05$.

Results: In all graphs produced from the simulations, we did not recover evidence of the "peas in pod" model reported in [1]. If the model planets followed the equally-sized and equally-spaced pattern, then they would have a linear slope of around 1 in all graphs and a high r^2. None of the graphs revealed a statistically significant correlation and had slopes significantly different from 1. Figures 1 and 2 show two of the graphs produced using the data from the Mercury code. The boundaries shown in Fig. 1 are artificial and created by the predetermined minimum size of the planetary embryos of the simulation (0.15 Earth masses), and the radius calculation was taken from [8].

Discussion: The model presented here shows insufficient agreement with the observations of [1]. There is not a strong tendency for adjacent planets to have similar masses. This suggests that stochastic accretion does not dominate planet growth in the CKS samples, but this work is very preliminary. To fully test the model we must consider the observational selection effects, including the efficiency with which embryos of various radii are detected at different orbital distances, and whether multiple planets in a system can be simultaneously detected in a transit survey, by comparing their mutual inclinations. A more careful analysis would consider only the most easily observed planets in each simulation. We will present these more carefully constructed analyses at the meeting.

We find comparisons between the peas-in-a-pod findings and the predicted planet mass and period ratios to be a useful measure of the success of a planet formation model. Our preliminary results point the way to comparisons between pure N-body models and models incorporating pebble accretion, that will allow us to assess the relative contributions of these modes.

Future work: We will consider the planetesimal data from multiple sources that form planets under different accretion conditions. We will put the data through a data reduction pipeline as close to identical as the one used in [1] to analyze the CKS data. We will determine which model produces planets with the closest similarities to the CKS system and to what extent the predictions align with the observations. This will guide future analysis of planetary formation processes and identify which processes are more likely to be at work in a young solar system.

References: [1] Weiss, L. M., et al. (2018), *AJ, 155:48*. [2] Kokubo, E, Ida, S (1998), Icarus, 131, 171 [3] Raymond, S. N., et al. (2004), Icarus, 168, 1–17. [4] Lambrechts, M. and Johansen, A. (2012), A&A, 544, A32. [5] Lambrechts, M., et al. (2014), A&A, 572, A35. [6] Chambers, J. E. (1999), MNRAS, 304, 793–799. [7] Kenyon, S, Bromley, B (2006), AJ, 131, 1837 [8] Chiang, E. and Laughlin, G. (2013), MNRAS, 431, 3444–3455. [9] Chen, J. and Kipping, D. M. (2017), MNRAS, 473, 2753–2759.

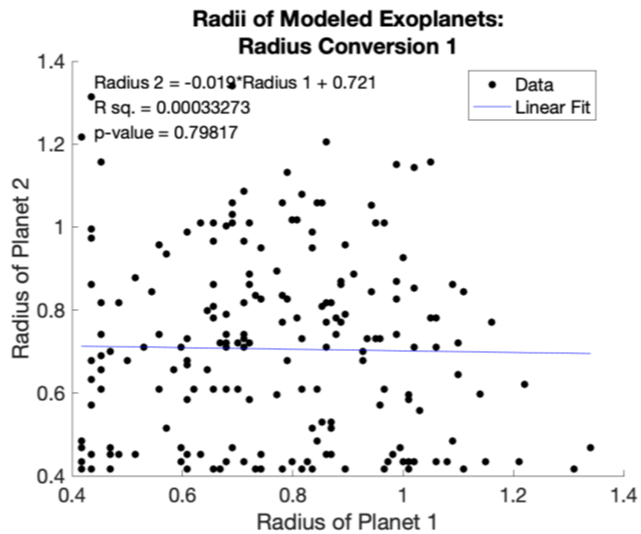

Figure 1: Plotting radius vs. radius of adjacent planets under one conversion calculation from mass to radius from [8]. This plot shows wide scatter and minimal correlation between the radii of planets within a pair, contrary to the results of [1].

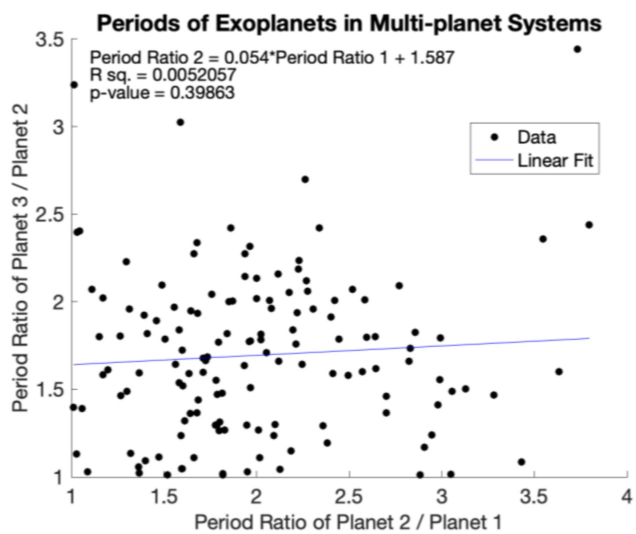

Figure 2: Plotting the period ratios of sequential planet pairs. This plot also shows wide scatter and minimal correlation between the radii of planets within a pair, contrary to the results of [1].