**RADIAL MIXING UNDER DIFFERENT ACCRETION SCENARIOS: OBSERVATIONAL CONSTRAINTS.** R. A. Fischer[1,2], F. Nimmo[2], and D. P. O'Brien[3], [1]Smithsonian National Museum of Natural History (fischerr@si.edu), [2]University of California Santa Cruz, [3]Planetary Science Institute.

**Introduction:** Knowing the provenance of the terrestrial planets is vital to our understanding of the origin, delivery, and abundances of their volatile elements; compositional and oxygen fugacity evolution during accretion, which influences the composition of planetary cores; and the early state of the protoplanetary disk. Here we investigate the influence of the gas giant planets' orbits on the provenance of the terrestrial planets and their volatile element budgets. By comparing our model to observations of elemental and isotopic ratios, we can better understand the early architecture of the Solar System and its effects.

**Observations:** Planetary volatile abundances are difficult to quantify, since many volatiles can partition into a planet's core (e.g., S, C) or deep mantle (e.g., H) in unknown abundances, while others are fractionated by crust formation (e.g., K). We use the K/U ratio as a proxy for bulk volatile content, because K is moderately volatile and U is refractory, while K and U are both extremely lithophile, similarly incompatible, and have been measured on a variety of Solar System bodies using gamma ray spectroscopy. Venus, Earth, and Mars show K/U ratios that may be interpreted as a linearly increasing trend with increasing heliocentric distance, or a constant value, within the large uncertainties of the measurements [1]. Volatile elements are expected to be enriched in the outer Solar System, so a linear trend would imply that these planets accreted from material originating near their present semimajor axes, while uniform K/U values across the terrestrial planets would imply strong mixing in the inner disk.

Other aspects of planetary composition have been used to check for a gradient of composition in the inner solar system, some of which show a correlation with heliocentric distance (e.g., Cr isotopes; [2]) and some of which do not (e.g., oxygen isotopes; [3]). The K/U ratio is a good tracer for mixing, because there are multiple lines of argument for an initial gradient in protoplanetary materials due to the volatility of K. There is no apparent $^{36}K/^{38}K$ fractionation across planetary materials, which limits the processes by which volatile loss could have occurred [4].

Ru is highly siderophile, so virtually all of the mantle's Ru was delivered in the late veneer, while Mo's lithophile behavior implies that the majority of Mo in Earth's mantle was delivered prior to the late veneer. $\varepsilon^{100}Ru$ and $\varepsilon^{92}Mo$ are linearly correlated in meteorites, and the silicate Earth also lies on this trend. This implies that Earth's Ru and Mo likely originated in the same isotopic reservoir, indicating that the late veneer had the same isotopic provenance as the bulk Earth [5–6]. This observation could be explained by complete mixing in the inner disk, which would homogenize isotopic anomalies [6], or by the late veneer having the same provenance as the bulk Earth.

**Modeling:** We have assessed the provenances of the terrestrial planets in *N*-body simulations with different Solar System architectures, to evaluate the relationship between orbital configuration and planetary feeding zones. We quantify the provenance of accreted material using the final mass-weighted semimajor axis (MWSMA), $\bar{a} = \frac{\sum_i m_i a_i}{\sum_i m_i}$, where $m_i$ and $a_i$ are the initial mass and initial semimajor axis, respectively, of each accreted body $i$. We used a suite of 100 *N*-body simulations from [7]. Fifty of the simulations were run with Jupiter and Saturn on more circular orbits (CJS), as predicted by the Nice model, and fifty were run with Jupiter and Saturn on more eccentric orbits (EJS), similar to their modern-day orbits. We also used a suite of 16 *N*-body simulations from [8], run under the Grand Tack paradigm, in which Jupiter and Saturn migrate inward and then outward [9].

**Results:** We have calculated the MWSMA for every planet that forms in the range 0–2 AU in the classical EJS and CJS cases (Figure 1a) and the Grand Tack model (Figure 1b). We find that while a planet's MWSMA is typically higher than its actual final semimajor axis in the EJS/CJS cases, there is a strong linear trend between the two, with planets forming at larger semimajor axes having larger MWSMA. In the Grand Tack model, we again find that a planet's MWSMA is typically higher than its actual final semimajor axis, but here there is a flat trend between the two, with planets having approximately the same MWSMA regardless of where they form. The Grand Tack model implies very strong radial mixing, producing a homogenous inner disk, while the classical EJS and CJS cases imply weak radial mixing, with planets accreting most of their material from near their final semimajor axes.

Figure 2 shows MWSMA values calculated only based on material that was accreted following the last giant impact (defined as the "late veneer"). In both classical and Grand Tack models, the late veneer on average originates from a higher MWSMA than the bulk planet, and in both cases, there is no significant trend between the MWSMA of the late veneer and the planet's final location, consistent with the idea of [10] of stochastic late accretion.

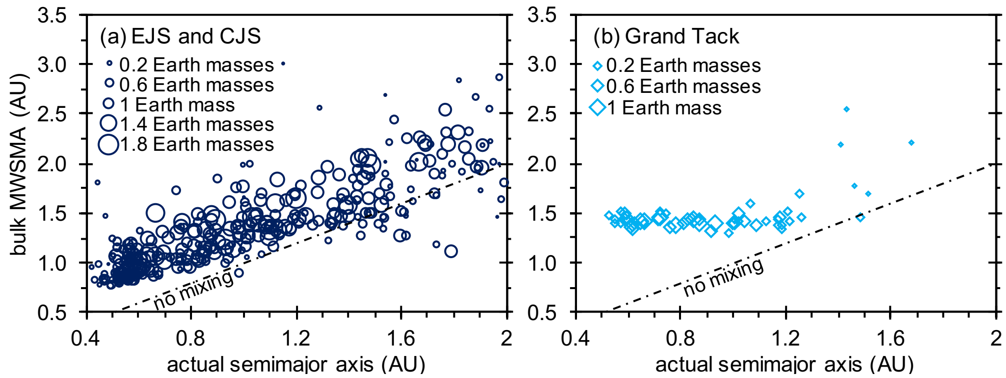


**Figure 1:** MWSMA of bulk planets formed in (a) 100 classical simulations (EJS and CJS cases) [7] or (b) 16 Grand Tack simulations [8]. Symbol size indicates planetary mass.

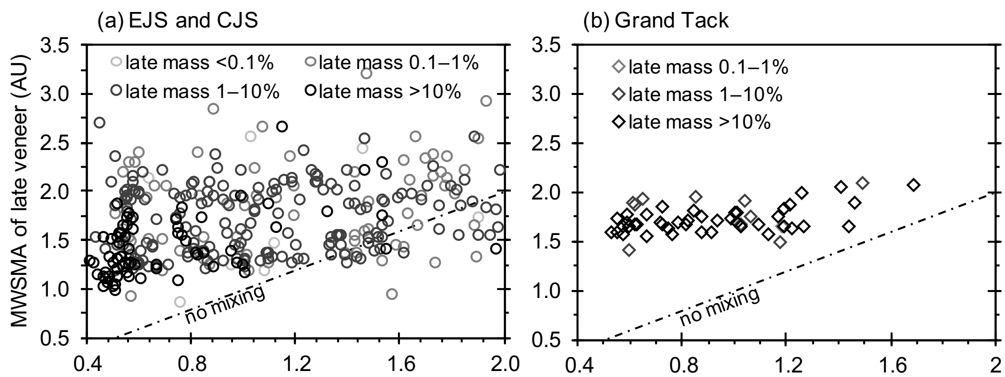


**Figure 2:** MWSMA of the late veneers of planets shown in Figure 1. Symbol color indicates the percentage of the planet's mass accreted after the last embryo.

**Discussion:** The classical Solar System architectures (i.e., EJS and CJS) and the Grand Tack model offer two distinct explanations for the observed K/U ratios and Ru–Mo isotope signatures of the terrestrial planets, with different testable predictions. Under a classical Solar System configuration, less radial mixing occurs during the main phase of planetary accretion. An initial gradient in K/U due to incomplete condensation, or preferential loss of K at smaller semimajor axes, accounts for the linear gradient in K/U between Venus, Earth, and Mars (Figure 1a). Alternatively, these classical models could be compatible with identical K/U ratios for the terrestrial planets if there was no initial gradient in K/U in the disk, though this scenario is less likely due to the volatility of K. In the Grand Tack model, a higher degree of radial mixing is predicted. This would result in the terrestrial planets having the same K/U ratio, which is consistent within uncertainty with observations.

Ru–Mo isotope systematics indicate that the bulk Earth and its late veneer have the same provenance, which can be quantified by the ratio $MWSMA_{bulk}/MWSMA_{late}$. In the EJS and CJS cases, planets forming in the range 0.75–1.25 AU have an average value of this ratio of $0.83 \pm 0.20$ ($1\sigma$). This ratio is unity within uncertainty, indicating that it is possible for the bulk Earth and its late veneer to have the same provenance in these models. In the Grand Tack case, this ratio is $0.83 \pm 0.06$, requiring an isotopically homogeneous disk near Earth's feeding zone.

These results allow us to make testable predictions about future measurements. EJS and CJS models imply that as we decrease the uncertainties on K/U for Venus and Mars, the trend across them will remain linearly increasing, while identical K/U ratios for the terrestrial planets would be more consistent with the Grand Tack model. In EJS and CJS cases, planets forming with semimajor axes of 1.25–2 AU have a ratio $MWSMA_{bulk}/MWSMA_{late} = 1.02 \pm 0.24$, indicating that Martian samples should also lie on the cosmic correlation trend for $\varepsilon^{100}$Ru and $\varepsilon^{92}$Mo. In the Grand Tack model, this ratio is $0.81 \pm 0.10$, implying that Martian samples are likely to not lie on the $\varepsilon^{100}$Ru–$\varepsilon^{92}$Mo trend, unless the inner disk is isotopically homogeneous even out to the Mars-forming region. The Grand Tack model also predicts shorter accretion timescales than the EJS and CJS cases [8], which may be testable with the Hf/W system or other chronometers [11].

**References:** [1] McCubbin F. M. et al. (2012) *GRL, 39,* L09202. [2] Lugmair G. W. and Shukolyukov A. (1998) *GCA, 62,* 2863–2886. [3] Mittlefehldt D. W. et al. (2008) *RiMG, 68,* 399–428. [4] Humayun M. and Clayton R. N. (1995) *GCA, 59,* 2131–2148. [5] Dauphas N. et al. (2004) *EPSL, 226,* 465–475. [6] Dauphas N. et al. (2014) *Phil. Trans. R. Soc. A, 372,* 20130244. [7] Fischer R. A. and Ciesla F. J. (2014) *EPSL, 392,* 28–38. [8] O'Brien D. P. et al. (2014) *Icarus, 239,* 74–84. [9] Walsh K. J. et al. (2011) *Nature, 475,* 206–209. [10] Bottke W. F. et al. (2010) *Science, 330,* 1527–1530. [11] Zube et al. (2016) LPSC.