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Headline Article

July 31, 2015

Making and Differentiating Planets



--- A detailed study forming Earth and differentiating it into core and mantle shows that it accreted heterogeneously and most water is added after 60% of the Earth had formed.

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The rocky planets formed by progressive aggregation of dust to make planetesimals which joined to make large objects called planetary embryos that finally accumulated into planets, one of which we live on. This chaotic process is complicated further by chemical changes with distance from the Sun, including differences in oxidation conditions and water concentration. Once the inner planets began to form, metallic iron sank to form cores, reacting with the rocky portions in the process. David C. Rubie (University of Bayreuth, Germany) and colleagues in Germany, France, and the United States put all this planetary action into an impressively thorough computer model of planet formation and differentiation. They show that the observed compositions of the Earth can be matched by simulations that include the Grand Tack (Jupiter and Saturn migrate inwards towards the Sun and then back out), and chemical gradients in the Solar System, with more reducing conditions near the Sun, more oxidizing farther from the Sun, and oxidizing and hydrated conditions even farther from the Sun. The study identifies other important variables, such as the extent to which metallic iron chemically equilibrated with the silicate making up the Earth's mantle, the pressure at which it happened, and the likelihood that Earth accreted heterogeneously.

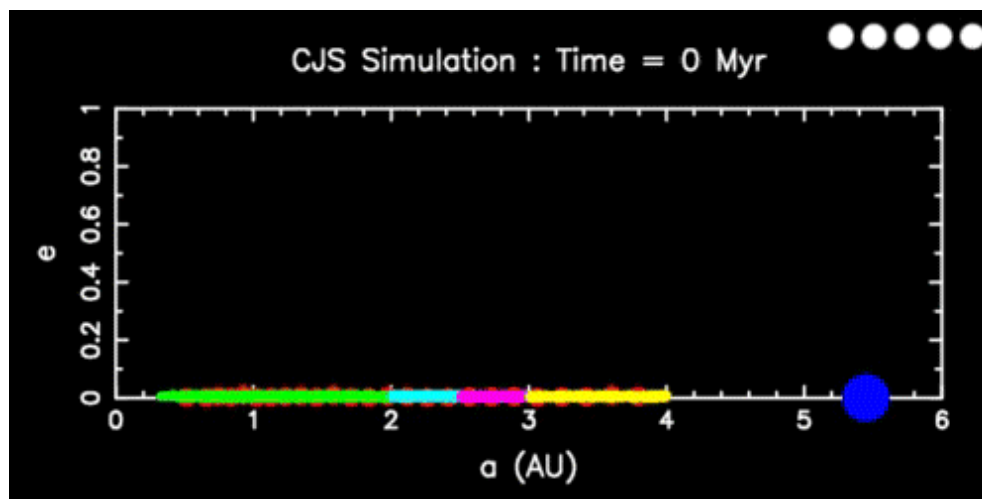
Reference:

- Rubie, D. C., Jacobson, S. A., Morbidelli, A., O'Brien, D. P., Young, E. D., de Vries, J., Nimmo, F., Palme, H., and Frost, D. J. (2015) Accretion and Differentiation of the Terrestrial Planets with Implications for the Compositions of Early-formed Solar System Bodies and Accretion of Water, *Icarus*, v. 248, p. 89-108, doi:10.1016/j.icarus.2014.10.015. [[abstract](#)]
- **PSRD presents:** Making and Differentiating Planets--[Short Slide Summary](#) (with accompanying notes).

Assembling Planets

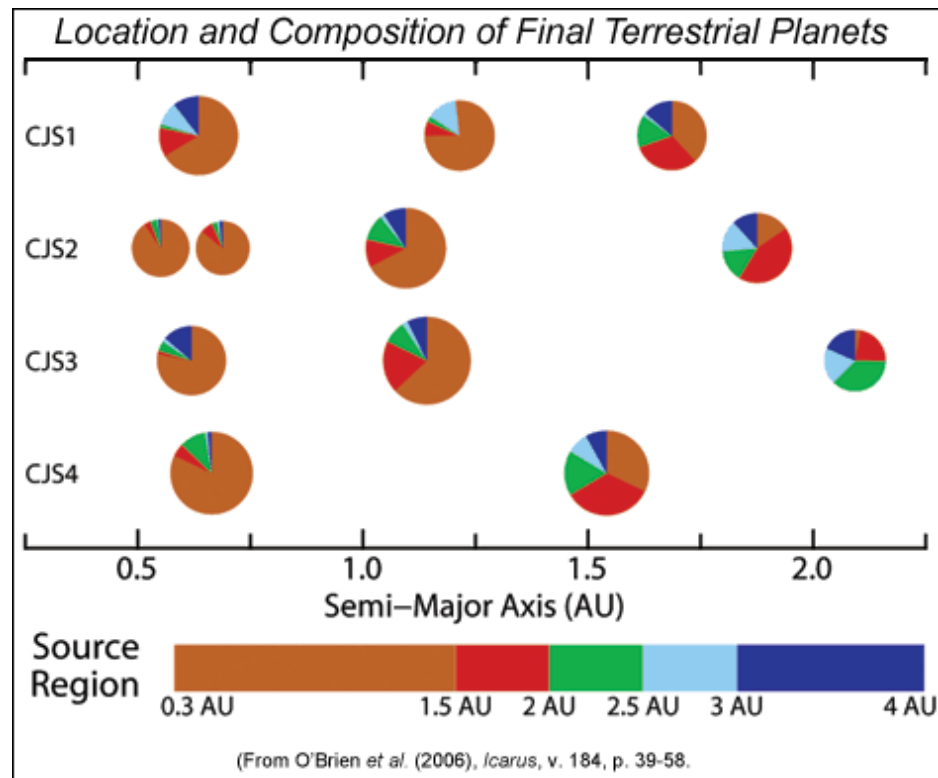
Planet formation is a messy business. Dust grains in the **solar nebula**, the dusty disk of gas surrounding the infant Sun, stuck to one another, making clumps that stuck to one another, which kept sticking as larger and larger objects assembled into objects kilometers to several kilometers across. These objects, called **planetesimals**, experienced a period of rapid growth, driven by the gravity fields of the largest, until a collection of hundreds of moon to Mars-sized planetary embryos (big planetesimals) orbited the Sun between what is now the region occupied by the inner planets and asteroid belt (0.3 to 4 **AU**). This set of embryos interacted with each other's gravity fields and the large fields of Jupiter and Saturn, slamming together at increasing speeds as they grew, eventually making the four inner planets we have in our Solar System. As an added dynamical bonus, Jupiter and Saturn may have migrated inwards and then outwards as the inner planets formed, an idea called the Grand Tack model.

Studies of how planets **accrete** from smaller objects have gotten progressively more sophisticated as computers have become faster and the codes that make digital planets inside of computers have become more efficient and more physically realistic. Examples of planet formation simulations are shown in **PSRD** article: **Dynamics and Chemistry of Planet Construction**, and shown in abbreviated form below. The simulation begins with half the mass in planetary embryos about the size of Mars and the other half in smaller planetesimals (1/40 the size of the embryos).

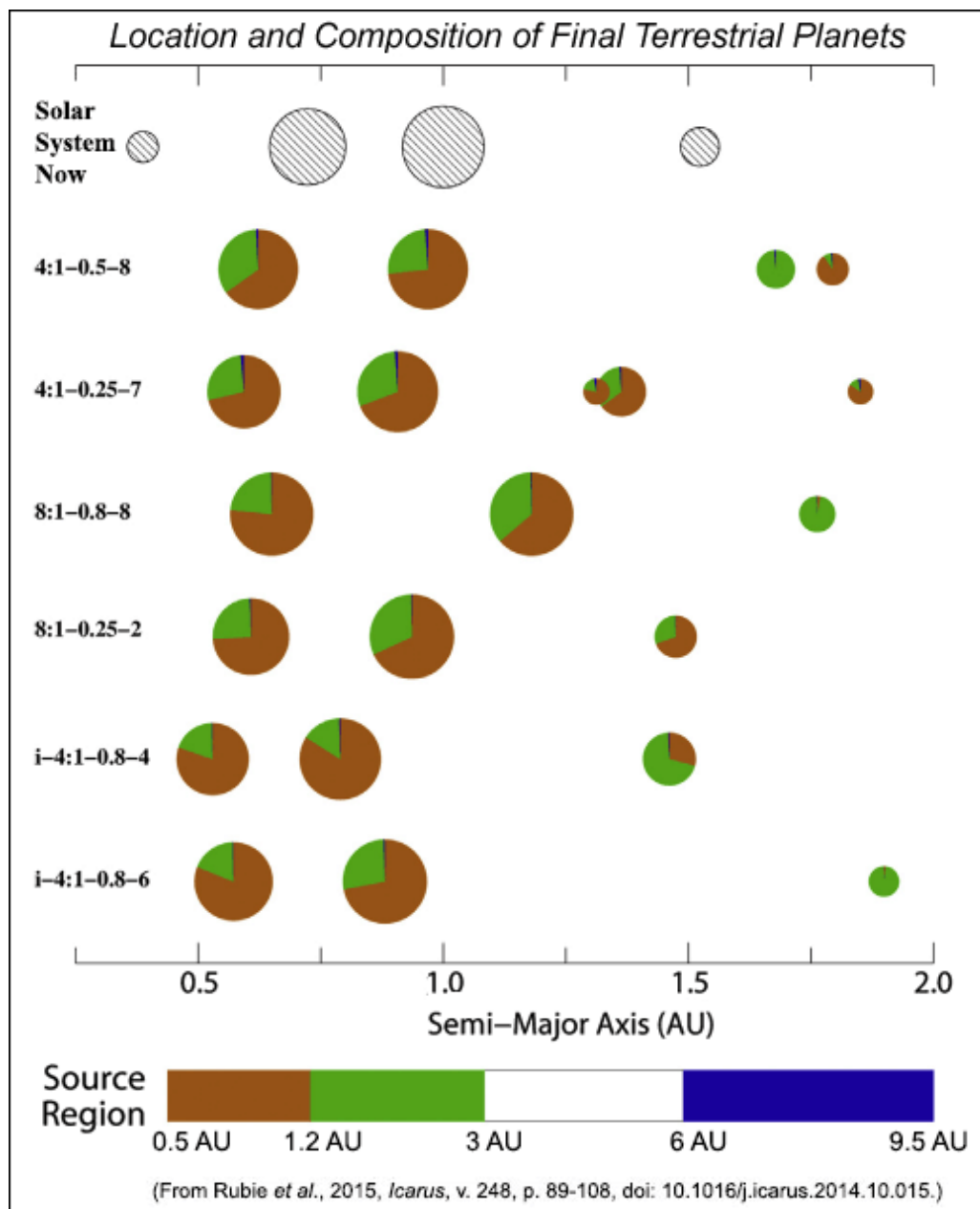


(Courtesy of David P. O'Brien, Planetary Science Institute, Tucson, AZ.)

[Top] This is one simulation by David O'Brien and colleagues. The plot shows distance from the Sun in AU versus the eccentricity, a measure of how egg-shaped an ellipse is. If the eccentricity is 0, the ellipse is a perfect circle. Starting with a thousand objects (planetesimals and larger planetary embryos), color-coded by their locations, gravitational interactions with each other and with Jupiter (big blue circle) cause the inner planets to grow. Note that three planets form in the terrestrial planet region, and that the sources of the accreting planetesimals come from a wide range of sources. This is shown in the rows of pie diagrams [Below] representing the outcomes of four different simulations, labeled CJS1 through CJS4.



There seems to have been a lot of mixing during planet formation, and Dave Rubie and his colleagues have tackled the difficult problem of trying to quantify the compositional effects of all that stirring in the inner Solar System. They used a set of planetary accretion simulations that included the Jupiter and Saturn Grand Tack, which severely limits accretion of planetesimals that were originally orbiting between 3 and 6 AU because the gravity fields of the big, tacking planets propel planetesimals out of the region. The results from six simulations are shown below. Note that the computer-generated inner planets are about the size of Earth and Venus and contain planetesimals from a range of starting regions, including the one that begins at 6 AU. Not all the simulations produce a Mars-sized object, but some do and they tend to be about the right size.



Results of six simulations by Rubie and coauthors that include the Grand Tack. Each row shows one simulation; numbers on the left are designations for the simulations. The diameter of each pie is proportional to a simulated planet's mass. The pie wedges indicate the zone from which planetesimals accreted. Although not easy to see, there is usually a small fraction from the blue region between 6 and 9.5 AU. This region is important because it is richer in volatile elements than those closer to the Sun. The simulations differ from each other in the mass distribution between planetesimals and planetary embryos, the mass of the largest embryo at the beginning of the simulation and the initial positions of the objects.

Chemical Composition of Simulated Planets

Just because a complicated computer code is capable of following a bunch of digital planetesimals and planetary embryos whacking into each other and accreting to progressively larger objects—the positions and sizes of which resemble our Solar System—does not mean that the simulations accurately depict what happened when the Solar System was forming. It would be good to have some tests. A particularly good check is to see if the simulations reproduce the chemical compositions of the planets, which we know particularly well from detailed studies of the Earth, and know reasonably well for Mars. Dave Rubie and his colleagues tackled this problem.

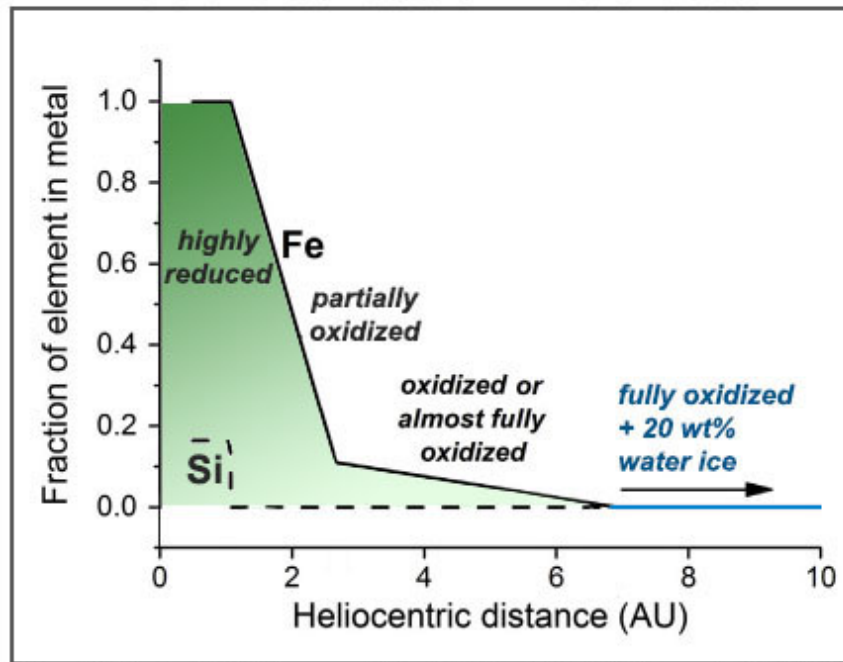
A complication is that we need to know how the composition of planetesimals vary with distance from the primitive Sun. Rubie shows that a critically-important chemical variable is the oxidation state, which dictates the relative abundance of reduced and oxidized iron. Some reduced iron must have been present in order to form metallic cores inside the otherwise rocky planets, but conditions cannot have been so reducing that most of the inventory of elements that make up rocks, such as silicon, ended up in the metallic cores.

Rubie and coworkers looked at four cases. The first involved uniform composition with distance from the Sun, using two different oxidation regimes. The second was a step function, with partially oxidized materials between the Sun and about 1 AU (this distance could be varied in the calculations) and reduced materials farther out. The third was the opposite of the second case: reduced materials near the Sun (about 1 AU, but the distance could be varied) and partially oxidized further out. The calculations included partitioning of **siderophile** elements (nickel, cobalt, and even a small amount of silicon if conditions were suitably reducing) into the metallic core, taking into account the pressure at which the partitioning from silicate to metal occurred and the amount of the rocky mantle involved.

These chemical gradients were then combined with the accretion simulations to estimate the compositions of the simulated Earths. They were optimized by changing the distance where the step in oxidizing conditions occurred, with the optimization criteria being how well the model Earth most closely matched the real one. Results for the uniform composition (homogeneous accretion) model and the step model with oxidized materials near the Sun did not come close to reproducing the terrestrial composition, so those models were rejected. The best results were obtained in the step model in which the near-Sun region was reducing, hence contained a lot of metallic iron, indicating that the regions closer to the Sun were more reducing than those farther out. This is consistent with the suggestion that iron meteorites, the melted cores of planetesimals that became asteroids, formed in the same region as Earth and the other rocky planets (see **PSRD** article: **Iron Meteorites as the Not-So-Distant Cousins of Earth**).

The two-step model with reducing conditions near the Sun and more oxidizing farther from the Sun did not precisely match the composition of the Earth, but were promising enough to inspire Rubie and coworkers to devise a more complicated scenario, as illustrated below. This model depicts an inner reduced zone that gradually becomes more oxidizing, a generally oxidized zone, and an outer, water-bearing zone. The wet outer zone would have its water mostly stored in planetesimals resembling CI and CM **carbonaceous chondrites**, which contain hydrous minerals such as clay minerals (also called **phyllosilicates**) and sulfates. (CI and CM chondrites began as mixtures of anhydrous minerals and ice. As they were heated by the decay of **radioactive** aluminum-26, the ice melted and the water reacted with the dry silicates to produce a complex array of minerals.) As Rubie and colleagues point out, H₂O is a good oxidant, ensuring that the planetesimal population becomes more oxidized as distance from the Sun increases.

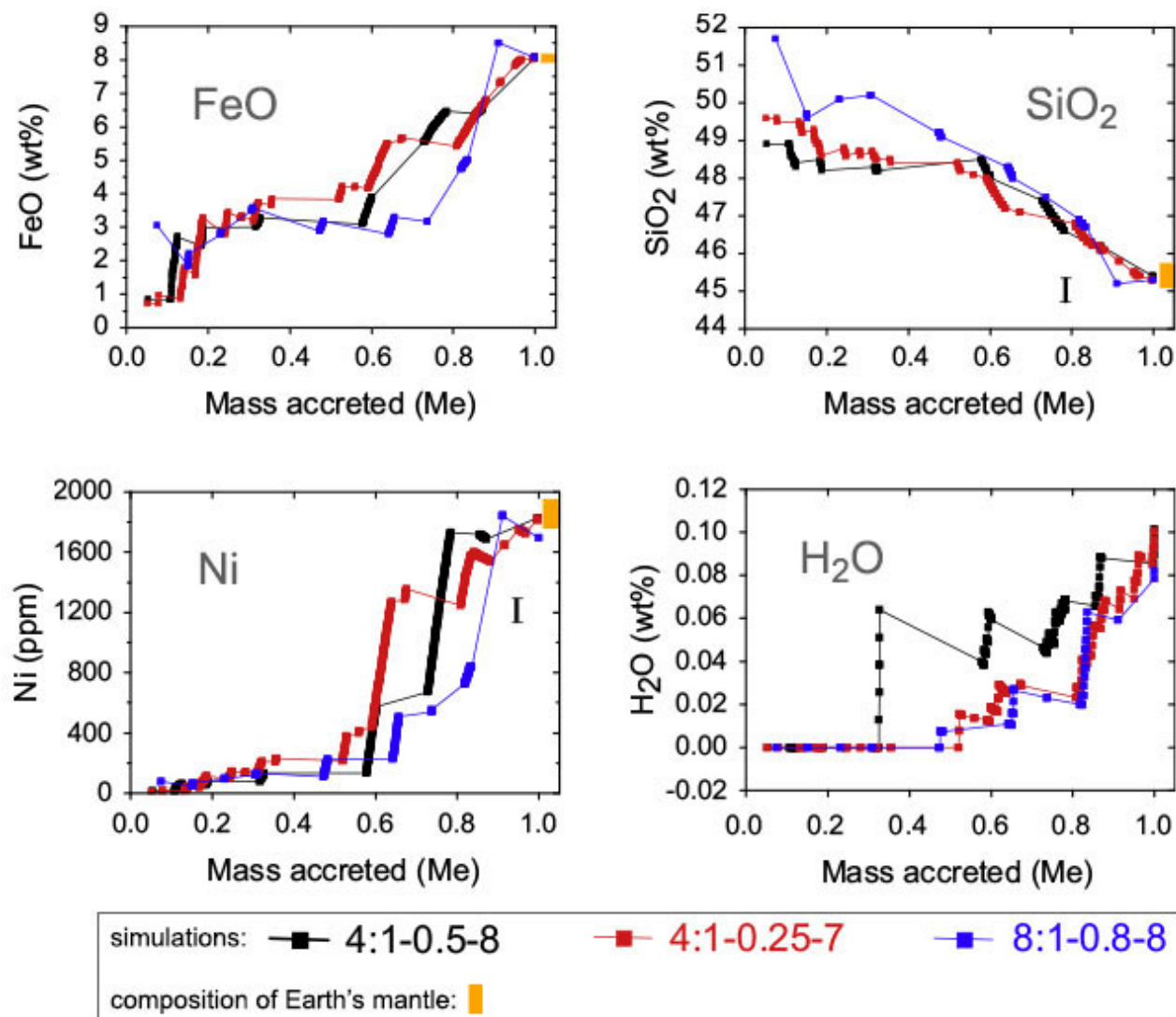
Initial Oxidation State of Primitive Bodies



(From Rubie *et al.*, 2015, *Icarus*, v. 248, p. 89-108, doi: 10.1016/j.icarus.2014.10.015.)

Variation in oxidation conditions (given by the fraction of iron in metal) versus distance from the Sun (in AU), with an outer zone that is fully oxidized and contains water. Calculations can vary the position of the first change in slope (higher or lower iron in metal, distance where the slope changes). There is also a region at about 1 AU from the Sun where silicon is reduced to metal; variables for this factor include the starting amount of total silicon that is reduced to metal and the distance at which silicon is completely oxidized. Another parameter is the distance from the Sun where water-bearing carbonaceous planetesimals exist. In the calculations, the distance at which the zone of water-bearing planetesimals begins is adjusted to result in approximately 1000 parts per million H₂O in the simulated Earth, matching most estimates for Earth's water content.

The chemical gradients were combined with the initial locations of the planetesimals and planetary embryos to show how elemental concentrations in the mantle changed as accretion took place to make the final simulated Earth. Examples are shown below. In the graphs, the gold bar shows the composition of Earth's mantle. It turns out that the first group of objects that built the Earth was from the reduced, inner zone. Consequently, the concentration of oxidized iron (FeO) increased as Earth grew. All the simulations show this trend. Related to this, the concentration of oxidized silicon (SiO₂) decreased because some was reduced and entered the metallic core. Note that nickel (Ni) is low in the mantle at first, but then grows as the accreting materials become more oxidized, finally reaching the amount determined from geochemical studies for the primitive Earth's mantle. (Rubie and coworkers show results for several other elements as well.) A particularly interesting result is that the calculations imply that Earth acquires most of its water after over half of the planet has accreted. The simulations also show that Earth could have accreted with its full complement of water, with no requirement to add any significant amount of water after the planet had formed.



(From Rubie *et al.*, 2015, *Icarus*, v. 248, p. 89-108, doi: 10.1016/j.icarus.2014.10.015.)

Variation of FeO, SiO₂, Ni, and H₂O in the simulated Earth mantle as the planet accreted for three different simulations (color coded). Actual primitive mantle values are shown with gold bars. Concentrations of FeO and Ni increase as more oxidized planetesimals and embryos merge with Earth. SiO₂ decreases because of reduction to metallic Si at first and then because the amount of oxidized iron increases in the mantle.

What about Venus and Mars? Rubie and cohorts did not focus on them, but the results show that simulated Venus ends up similar to Earth, as expected. The composition of Mars, on the other hand, depends on the exact location of the original embryo that built up to Mars size. Too close to 1 AU and Mars is deficient in FeO. Too far out and it gets too much. Nevertheless, it is a good start.

A Multifaceted Approach

Dave Rubie and his associates have boldly tackled the combination of the dynamics of planetary accretion, **differentiation**, and compositions of the mantles of the inner planets. Such interdisciplinary research is essential to fully understand planet construction and to identify the most important processes involved. Rubie and coworkers find that oxidation state is important and it happens because of inward migration of ice. The work also highlights the possibility that the water delivered to the inner planets originated in planetesimals formed beyond the present orbit of Jupiter, which further emphasizes that mixing was an important process in the early Solar System.

Earth's composition has been determined by decades of careful geochemical and geophysical studies, and the models by Rubie and coauthors produce good matches to the known composition. Nevertheless, detailed study of siderophile elements in the mantle suggest that these elements were added after core formation, indicating a role for the addition of some chemical components after Earth had essentially been fully constructed, although the siderophile element concentrations can be modeled by core formation at a range of pressures. See, for example, **PSRD** CosmoSpark report: **Making an Argument Against the Late Veneer Hypothesis for Mars**. Of course, there is no fundamental reason why late addition of materials cannot be the icing on a cake baked by planetary accretion and its accompanying mixing of reduced, oxidized, and wet ingredients.

The research by Dave Rubie and coauthors, highlighted in this **PSRD** article, was supported by the European Research Council (ERC).

Additional Resources

Links open in a new window.

- **PSRDpresents:** Making and Differentiating Planets--**Short Slide Summary** (with accompanying notes).
- Bottke, W. F. and Martel, L. M. V. (2006) Iron Meteorites as the Not-So-Distant Cousins of Earth, *Planetary Science Research Discoveries*, <http://www.psrд.hawaii.edu/July06/asteroidGatecrashers.html>. [**PSRD article**]
- Martel, L. M. V. (2015) Making an Argument Against the Late Veneer Hypothesis for Mars, *Planetary Science Research Discoveries*, <http://www.psrд.hawaii.edu/CosmoSparks/May15/HSE-highPT.html>. [**PSRD CosmoSparks report**]
- O'Brien, D. P., Morbidelli, A., and Levison, H. F. (2006) Terrestrial Planet Formation with Strong Dynamical Friction, *Icarus*, v. 184, p. 39-58. doi:10.1016/j.icarus.2006.04.005. [**abstract**]
- Rubie, D. C., Jacobson, S. A., Morbidelli, A., O'Brien, D. P., Young, E. D., de Vries, J., Nimmo, F., Palme, H., and Frost, D. J. (2015) Accretion and Differentiation of the Terrestrial Planets with Implications for the Compositions of Early-formed Solar System Bodies and Accretion of Water, *Icarus*, v. 248, p. 89-108, doi:10.1016/j.icarus.2014.10.015. [**abstract**]
- Taylor, G. J. (2010) Dynamics and Chemistry of Planet Construction, *Planetary Science Research Discoveries*, <http://www.psrд.hawaii.edu/Mar10/PlanetConstruction.html>. [**PSRD article**]
- Walsh, K. J., Morbidelli, A., Raymond, S. N., O'Brien, D. P., and Mandell, A. M. (2011) A Low Mass for Mars from Jupiter's Early Gas-driven Migration, *Nature*, v. 475, p. 206-209, doi:10.1038/nature10201. [**abstract**]



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