How Does Accretion Influence Planetary Differentiation?: Feed Forward from the Accretion Conference to the Differentiation Conference

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The Lunar and Planetary Institute’s First Billion Years topical initiative [1] focuses on the major processes that shaped the early history of the Solar System’s planetary bodies, including accretion, differentiation, bombardment, and the development of habitable environments. An important aspect of the First Billion Years initiative is to understand the interplay between these processes. Because accretion and differentiation at least partially overlapped in time during early Solar System history, the style and rate of accretion must have influenced early planetary differentiation.

The authors of this abstract are members of the Science Organizing Committee for the forthcoming LPI Planetary Differentiation topical conference (planned for spring 2018). The goal of this abstract is to illustrate some of the ways in which accretion sets the stage for planetary differentiation, as well as how the existence of differentiated bodies constrains accretion rates. In addition to the ideas described here, we are interested in the varying perspectives of the participants in the Accretion topical conference about the dominant mechanisms and rates of accretion in various parts of the Solar System. Our objective is to carry a report of the major conclusions (and their associated uncertainties) from the Accretion conference forward as input to the Differentiation conference.

Timescales of Accretion and Differentiation

A broad range of accretion models exist in the literature ([2] provides a recent review). These range from models in which planetesimals gradually accrete to form planetary embryos [3-5] to more recent “pebble accretion” models in which meter-scale planetesimals very rapidly aggregate into planetary embryos [6]. In addition, some models incorporate varying amounts and rates of radial migration of Jupiter and Saturn through the solar nebula (the Nice model [7] and the Grand Tack model [8, 9]). Because small objects cool more rapidly than large objects, and because planetary differentiation requires reaching internal temperatures exceeding 1000 °C, the rate of accretion in the various classes of accretion models may have important implications for the ability of planetesimals and planetary embryos to differentiate. Thus, constraints on how rapidly planetesimals grow from kilometer scale to 100-1000 km scale in the various accretion scenarios and how the growth rate varies with distance from the Sun are important inputs to differentiation modelers.

For small (asteroid-size) objects, the primary energy source for melting and differentiation is radioactive decay of 26Al (half-life 0.73 million years) and 60Fe (half-life 2.6 million years). Melting and differentiation of dry objects requires accretion in less than 2 million years [10]. Thus, the very existence of differentiated silicate bodies such as the eucrite parent body (the asteroid Vesta, radius 263 km) and the angrite and urelite parent bodies [11–13] constrains the rate of accretion for at least some objects. Short lived radiometric chronometers, such as 182Hf-182W (which measures the separation of metal from silicate), also requires rapid accretion. Core formation on the angrite parent body occurred within 2 million years of CAI formation [14] and within 3.3 million years of CAI formation on the urelite parent body [15]. Melting in the parent bodies of five different classes of iron meteorites occurred with 0.6 million years of CAI formation [16]. Rapid accretion may also have been required further from the Sun, as models for the despinning of Saturn’s satellite Iapetus have been interpreted as requiring formation within 5 million years of CAI formation [17]. Similarly, results from the Dawn mission indicate that Ceres had to accrete in less than 5 million years [18].

Mixing in the Solar Nebula and the Existence and Preservation of Distinct Chemical Reservoirs

It is generally accepted that the decrease in temperature with distance from the Sun resulted in a chemical composition gradient in the solar nebula, with volatile-depleted materials in the innermost Solar System (similar to enstatite chondrites) and increasingly volatile-rich materials (ordinary chondrites and carbonaceous chondrites) at greater distances. Superimposed on this gradient, a sharp division into inner versus outer Solar System materials [19, 20]
may have been maintained by the early presence of Jupiter [21]. In spite of this initial composition gradient, radial mixing during accretion likely caused all four of the terrestrial planets to incorporate some material from each of these compositional zones [22], partially erasing the original composition gradient. However, numerical modeling does not predict that the resulting planets will all be compositionally identical, and the existence of distinct isotopic compositions (particularly oxygen, chromium, and titanium [9, 19, 23]) in the Earth and various meteorite classes clearly demonstrates that radial mixing in the nebula was incomplete.

One effect of these compositional differences is on core differentiation. There is a gradient in oxygen fugacity ($f\text{O}_2$) between the various nebula chemical reservoirs, ranging from low $f\text{O}_2$ in the enstatite chondrite reservoir toward increasingly higher $f\text{O}_2$ in the ordinary chondrite and carbonaceous chondrite reservoirs [23, 24]. This is important for core size, because at low $f\text{O}_2$ most iron will be in the form of metallic Fe, resulting in larger cores, whereas increasing the $f\text{O}_2$ will result in more Fe as FeO in silicates, resulting in smaller cores and thicker mantles.

Accretion-related chemical composition differences among planets may also influence their long-term volcanic histories. Even subtle differences in composition between the various planets can have substantial effects on the differentiation and long-term volcanic histories. For example, the best models for the chemical compositions of the bulk silicate Earth [25] and Mars [26] indicate differences in the magnesium number and the alkali contents of the two planets (Earth: Mg# 89, Na$_2$O 0.35 wt. %, K 260 ppm; Mars: Mg# 80, Na$_2$O 0.50 wt. %, K 305 ppm). These differences are important, because the Mg# and the alkali abundance are the two strongest controls of the silicate solidus in the mantle (lower Mg# and higher Na reduce the solidus) and because $^{40}$K is an important radioactive heat source, particularly early in Solar System history. The differences between Earth and Mars result in a lower mantle solidus and greater radioactive heating on Mars and thus in greater crustal production on Mars. With all other factors held constant, just making these small changes in composition can change the long-term crustal production on Mars by 20% [27].