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Planetesimals

BENJAMIN P. WEISS

This book is about planetesimals, small, rocky, and icy planetary bodies that formed and evolved in the early solar system. Planetesimals play at least two important roles in planetary science. First, as the first generation of planetary objects, they served as the fundamental building blocks of planets. Intermediate in size between centimeter-sized pebbles and 1000-kilometer-sized planetary embryos, they represent a critical but still enigmatic stage in planetary growth. Because the formation of kilometer-sized bodies is difficult to understand given the likelihood of erosive mutual collisions and rapid orbital evolution due to gas drag, solving this problem will provide fundamental constraints on the sizes of accreting bodies, the nature of turbulence in the nebula, and the intensity of nebular magnetic fields. Second, planetesimals, and their modern day relics – asteroids, comets and Kuiper-belt objects – are fascinating planetary worlds in their own right. They experienced a much broader range of thermal histories than planets; these diverse conditions produced a diversity of igneous end states, from unmelted bodies, to partially melted bodies, to fully molten and differentiated objects. Furthermore, their geologic evolution and internal structures were fundamentally sculpted by impacts and mutual collisions. In many ways, planetesimals are like the planets they became, but in other ways they are very unfamiliar places.

The word “planetesimal,” a compounding of “planet” and “infinitesimal” (OED Online, 2016), came into common usage in the first decade of the twentieth century following Chamberlin’s proposal that the planets accreted from small, primordial solid bodies (Chamberlin, 1904). His concept of a planetesimal precursor for planets was in opposition to the eighteenth century hypothesis of Laplace (1796) that solar system bodies condensed directly out of a hot gas (Brush, 2006). As small, primitive bodies, planetesimals were naturally identified as the parent bodies of meteorites. As a result, from their conceptual inception as both extraterrestrial bodies and the sources of meteorites, planetesimals have spanned the fields of astronomy and geology and are a central focus of modern planetary science.

The chapters in this book reflect this interdisciplinarity. In Chapter 2, Erik Asphaug reviews the role of impacts in forming, scrambling and sometimes even obliterating planetesimals. He describes a kind of collision rarely encountered by planets but which was common amongst planetesimals because of their smaller and, typically, mutually similar sizes. These “hit-and-run” collisions may play a key role in producing the astonishing compositional and structural diversity of planetesimals, which ranged from icy, to rocky, to nearly pure iron worlds. As described by William Bottke and Alessandro Morbidelli in Chapter 3, the collisional evolution of planetesimals both specified and was determined by the size and spatial distribution of planetesimals in the early solar system. Therefore, reconstructing the initial size–frequency distribution of planetesimals is essential for understanding the role that collisions played in regulating the planetesimal population and forming planets. Bottke and Morbidelli discuss how a diversity of datasets, including the present-day size-frequency distribution of the asteroid belt, asteroid families (the remnants of catastrophically disaggregated asteroid), and craters on asteroids and the Moon, can be used to constrain the planetesimal population and, by implication, the migration and evolution of the planets.

The chemical and mineralogical diversity of planetesimals and the spectrum of differentiation end states is explored in the next five chapters. Timothy McCoy and Emma Bullock discuss in Chapter 4 how the melting and differentiation of planetesimals is controlled by the size of the body, its temperature (which relates to formation time due to the influence of radiogenic heating), the relative abundance of rock and ice, and the oxygen fugacity. They then discuss the particular case of low-oxygen fugacity enstatite chondrites and achondrites and their implications for the formation and evolution of Mercury. In Chapter 5, Julie Castillo-Rogez and Edward Young instead focus on planetesimals with higher ratios of rock to ice. Represented by carbonaceous bodies in the asteroid belt today, many of these bodies experienced extensive aqueous alteration, modest heating from the decay of short-lived radionuclides, and possibly even partial differentiation that produced structural layers of ices, salts, and variably dehydrated rock. Roger Fu and colleagues explain in Chapter 6 how differentiation often proceeded well beyond ice-melting and aqueous fluid flow to silicate melting and metallic core formation. Unmelted and melted bodies would be the sources of chondritic and achondritic meteorites, respectively. The modest temperatures and inefficiency of upward silicate melt migration on some bodies suggests that some may have never reached liquidus temperatures throughout, leading to the formation of partially differentiated bodies. Such an object could be the sources of both chondrites and achondrites.

Bodies that formed fully differentiated structures in some ways resembled that of planets and in other ways were distinctively different. Alex Ruzicka and

colleagues describe in Chapter 7 our current understanding of the enigmatic iron and stony-iron meteorites. Unlike any known planetary samples, many of these meteorites are derived from planetesimal cores and so provide a unique window onto planetary core processes in general. However, because liberation of these samples from their parent bodies required catastrophic collisions, they have been impact-modified in complex and as yet poorly understood ways. Lionel Wilson and Klaus Keil discuss in Chapter 8 how early melting on planetesimals may differ fundamentally from that of larger bodies in that global oceans of magma may have never formed due to the upward migration of melt toward the surface. Thus, unlike Moon-sized and larger objects, which inevitably formed large regions of surface melt due to their enormous gravitational energy of formation, only small fractions of planetesimals may have been molten at any given time.

As described in Chapter 9 by Aaron Scheinberg and colleagues, it has recently been realized that some of these bodies even generated dynamo magnetic fields in their advecting metallic cores, analogous to the Earth's magnetism. These planetesimal dynamos, long since extinct, may have been powered by core crystallization (like that of the Earth today), thermal convection, or perhaps even mechanical stirring by wobbling of the silicate mantle following an impact. Richard Harrison and colleagues discuss in Chapter 10 how planetesimal dynamos, although short-lived, were likely widespread among early solar system planetesimals given their rapid cooling rates and the power available from core crystallization. Dynamos have now been identified on the parent bodies of basaltic achondrites, stony-iron meteorites, and even some carbonaceous chondrites.

The next two chapters discuss the isotopic record of planetesimals as recorded in meteorites. In Chapter 11, Thorsten Kleine and Meenakshi Wadhwa show how radiogenic isotopes of tungsten, chromium, and aluminum can constrain the timing of planetesimal core formation and silicate melt extraction. In Chapter 12, Anat Shahar and colleagues review how stable isotopes of iron, silicon, and zinc may constrain metallic core formation, early volatile depletion events, and possibly even the bulk composition of the bodies.

The next four chapters discuss the small-body and astronomical record of planetesimals. As reviewed in Chapter 13 by Pierre Vernazza and Pierre Beck, asteroids, comets, and Kuiper-belt objects exhibit a tremendous range of compositions that vary as a function of distance from the Sun. This compositional variation constrains the dynamical evolution of the primordial planetesimal reservoir. Thomas Burbine and colleagues in Chapter 14 discuss how asteroid families, the disaggregated fragments of a collisionally shattered large asteroid, provide a natural stratigraphic cross-section of planetesimal interiors. Among the more than 100 recognized families, a diversity of differentiation end states is observed, from undifferentiated, to partially differentiated, to fully differentiated. This mirrors the

meteorites in range, but the fractionation of differentiated families is much less than what is observed among meteorite groups. In Chapter 15, Carol Raymond and colleagues describe in detail exploration of the largest intact differentiated asteroid, Vesta. The mission has confirmed that Vesta is the parent body of the howardite–eucrite–diogenite meteorites and has a fully differentiated structure including a metallic core. Andrew Youdin and George Rieke review in Chapter 16 what we currently know about planetesimals in exoplanetary systems as they transition into asteroids. Astronomical observations of these systems offer the exciting possibility of studying the collisional and accretional evolution of these bodies that until now has mainly been inferred from meteorite studies and observations of the present-day asteroid belt in our own solar system.

Finally, in Chapter 17, Linda Elkins-Tanton discusses the consequences of planetesimals for the planets into which they coalesced. She describes how the volatile contents of the planets may depend intimately on the ability of planetesimals to retain their volatile elements against exhalation to space, which in turn depends on their size and formation time. She also shows how the size of the terrestrial planets' metallic cores reflects the iron abundances in planetesimals and their oxidation state as well as their impact histories.

All told, the early solar system, with its swarm of magmatically and magnetically active planetesimals, its plethora of alternatively catastrophic and accretionary impacts, and its growing and differentiating large planetary bodies, was an energetic and dynamic place. We hope this book both captures some of this excitement and lifts a little of its mystery.

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