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Planetesimals

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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 chapter 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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More Information

Part One

Dynamical Evolution

2

Signatures of Hit-and-run Collisions

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2.1 Introduction

Terrestrial planets grew in a series of similar-sized collisions (SSCs) that swept up most of the next-largest bodies (NLBs; see Box 2.1). Theia was accreted by the Earth to form the Moon according to the theory. Planetesimals likewise might have finished their accretion in a sequence of "junior giant impacts," scaled down in size and velocity. Here we consider the complicated physics of pairwise accretion, as planetesimals collide and grow to planetary scales, and show how the inefficiency of that process is a foundation for the origin of planetesimals and the diversity of meteorites and primary asteroids.

Detailed simulations show that planetary collisions are inefficient mergers. Accretion inefficiency gets concentrated, as it were, in the unaccreted bits and pieces, giving asteroids and meteorites their distinctive record, according to the

Box 2.1
Symbols and acronyms used in this review; see also Figure 2.3

SSC = similar-sized collision ($R_1 \sim R_2$, $v_{rel} \sim v_{esc}$),
HRC = hit-and-run collision ($\xi \sim 0$)
NLB = next-largest bodies, the most massive contributors to the largest bodies
$\boldsymbol{N_{final}}$ = last unaccreted NLBs, of $N \gg N_{final}$
GMC = graze-and-merge collision ($\xi \rightarrow 1$)
SFD = size frequency distribution, $dn \sim R^{-\alpha} dR$
$\boldsymbol{\xi}$ = accretion efficiency, $(M_F - M_1)/M_2 \leq 1$
$\boldsymbol{h}$ = number of HRCs experienced by a feedstock NLB
$\boldsymbol{a}$ = magnitude of attrition, $\ln(N/N_{final})$
$\boldsymbol{\phi}$ = scaled relative velocity v_{rel}/v_{esc}
$\boldsymbol{\gamma}$ = normalized projectile mass $M_2/(M_1+M_2)$
$\boldsymbol{\theta}$ = impact angle at contact, $\sin^{-1}[b/(R_1+R_2)]$, b = impact parameter
$\boldsymbol{M_2'}$ = most massive identifiable remnant of M_2 (e.g. core)

arguments below. The impact axis is well off-center in a typical collision, relative to the combined center of mass, with dire consequences to the less massive object M_2. The target M_1 serves both as an "anvil" into which M_2 collides, and decelerates, and as a gravitational pivot around which it gets swung, causing it to be shredded.

The post-collision system can be gravitationally bound or not, depending on the projectile mass $\gamma = M_2/(M_1 + M_2)$ normalized to the total mass, the relative velocity v_{rel} normalized to the escape velocity v_{esc}, which scales with size, the impact angle θ with median value 45°, and composition, differentiation, rotation, and thermal state. Outcomes of SSCs are diverse throughout this large parameter space, segregating what is gravitationally bound from what is not, thereby causing the disruption and compositional segregation of planetesimals and growing planets.

For example, the standard model of Moon formation involves a graze-and-merge collision (GMC) where a Mars-size planet Theia is mostly accreted ($\xi \sim 1$) by a ~45° impact into proto-Earth at close to the mutual escape velocity v_{esc} (Canup and Asphaug, 2001), leaving a silicate protolunar disk. The Mars hemispheric dichotomy might have been caused by a faster (up to $2v_{esc}$) collision (Marinova *et al.*, 2008), in which case the impactor was not accreted by M_1.

Consider the general case of similar-size embryos or planetesimals orbiting the Sun. In the absence of drag they will be excited by mutual gravitational encounters, increasing their characteristic encounter velocities to $v_{rel} \sim v_{esc}$ (Safronov and Zvjagina, 1969). Their impact velocity is $v_{imp}{}^2 = v_{esc}{}^2 + v_{rel}{}^2$, so of order $\sqrt{2}$ faster than v_{esc}. For this value (as shown below) about half of SSCs end up with too much angular momentum and too much impact energy to result in effective merger. Mantle-stripped cores, stranded clumps, and dispersed sheets become the norm, broadly classified as hit-and-run collisions (HRCs) when most of M_2 escapes in recognizable form (see Bonsor *et al.*, 2015). A typical HRC results in one or more massive bodies escaping from M_1, for example a core fragment $M_2' < M_2$, along with clumps, arms, and plumes of escaped crust and upper mantle materials. Other HRCs are super-catastrophic, transforming M_2 into an escaping clumpy plume; here the outcome is sensitive to the thermodynamic accuracy of the simulation and unexplored effects related to melt segregation and degassing.

The mantle-stripping and catastrophic disruption of M_2 in about half of events can explain how massive planetesimals were destroyed by the planets that were trying to accrete them. The HRC hypothesis can also explain, in a statistical argument, how disruption byproducts disappeared, the "missing mantle" paradox (Burbine *et al.,* 1996). It also predicts lots of orphan asteroids, without parent bodies. Consider a very idealized HRC that produces one stripped core (M_2'), 10 mantle clumps, and thousands of bits, and leaves M_1 pretty much the same.

The orbits of these bodies intersect, so their probability of colliding with one another is high. Their further sweep up is likely, and so is collisional grinding. Sweep-up is strongly biased to favor the most massive object M_1, because of size and gravitational focusing. Now suppose M_1 sweeps up 90% of the remnants in a size-independent process, at random. Nine times out of ten, M_2' is one of the bodies accreted by M_1 and disappears; removing $^9/_{10}$ of the rest leaves one orphaned mantle clump, without a parent asteroid, and hundreds of bits.

One time in ten, according to these assumptions, M_2' is not accreted by M_1, so it persists as a modern riddle. On average its lost mantle clumps and exterior bits are accreted with 90% efficiency by M_1, so that is the sink for its missing mantle. This leads to a dichotomy between "accreted" and "unaccreted" populations. The accreted become dominant in mass, and nominal in bulk composition (e.g. "chondritic"). The unaccreted remain next-largest (or smaller) and develop a remarkable diversity of characteristics by surviving multiple HRCs. These concepts are expanded upon below.

2.1.1 Final Accretion

In a typical *N*-body dynamical simulation of terrestrial planet formation, dozens to hundreds of embryos (mass M, radius R) orbit the Sun; mutual perturbations lead to chaos and intersecting trajectories. Two bodies collide when their center-of-mass separation distance $r < R_1 + R_2$. A hierarchy of orbital collisions, treated as perfect mergers, can produce Venus- and Earth-mass "chondritic" planets in simulations (e.g. Chambers and Wetherill, 1998; Raymond *et al.*, 2007), plus a few unaccreted objects thought to represent Mercury and Mars. This is the "late stage" of giant impacts (Wetherill, 1985). Likewise, the massive planetesimals in the main belt, and the oligarchic precursors to planets, are thought to have accreted by hundreds of scaled-down SSCs, for instance 300–500-km-diameter bodies colliding at ~1 km s^{-1} to produce 500–1000-km bodies.

For expediency, final accretion is approximated in *N*-body dynamical simulations as a series of perfect mergers, starting from (say) 100 or so planetary embryos orbiting the Sun. Larger *N* (thousands) can be studied, either by increasing each planetesimal cross-section artificially by 10–100 to speed up the mergers (they do not even have to hit, to stick) or by limiting mutual encounters to the few largest bodies. Collisional physics gets swept under the rug. In particular, the premise of perfect sticking requires a gravitating body to acquire arbitrary angular momentum. Tracking *N*-body encounters, Agnor *et al.* (1999) showed that this often results in terrestrial planets spinning faster than P_{rot} ~1 hr, greatly exceeding the spin-disruption threshold (Chandrasekhar, 1969). This is sometimes taken to support the viability of Moon-formation scenarios like Darwin (1879), starting with a proto-Earth spinning near the brink of disruption. But the actual implication is that perfect mergers are unphysical.

The complex interactive dynamics of SSCs requires three-dimensional computational modeling. The most common method is smooth particle hydrodynamics (SPH), originally applied to studies of the Moon-forming giant impact (e.g. Benz *et al.*, 1989). Early general studies of the parameter space of SSCs (Agnor and Asphaug, 2004; Asphaug *et al.*, 2006) were limited to Mars-sized targets and Moon- to Mars-size projectiles, from v_{rel} = 1–3v_{esc} and impact angles 0°, 30°, 45°, 60° (equally probable quadrants; see Figure 2.4 below). They found that limits on angular-momentum acquisition place strong limits on mass acquisition, with final spin periods no shorter than ~4 hours, and much of M_2 continuing downrange (HRC) in about half of the simulations. Agnor and Asphaug (2004) suggested that this inefficiency would double the timescale of terrestrial planet formation. The first *N*-body study to track HRC remnants (Chambers, 2013) found that the timescale does increase, to 160 Ma or longer, which is consistent with modern ideas (reviewed in Nimmo and Kleine, 2015) for a late-forming Moon and a long tail of final collisions.

Concerning planetesimals, evidence for their collisional accretion is found in the largest asteroids, whose diversity is even more extreme than the terrestrial planets. A principal distinction is that accretion in the main belt was lossy by a factor of 100 or more; most of the starting mass was eroded or scattered by some upheaval. Extrapolating the protoplanetary disk between Mars and Jupiter suggests an original mass ~0.1–1$M_{\oplus}$ (Weidenschilling, 1977, Farinella *et al.*, 1982). Of the 0.1–1% that remains, half is found in five 300–1000-km asteroids that range in bulk density from ρ ~ 2–4 g cm^{-3}, and represent three or four unique spectroscopic classes (e.g. DeMeo *et al.*, 2009). Such phenomenal diversity is not expected for a relatively narrow region of the nebula. The remnant of the mass is a grab-bag of thousands of objects with complex taxonomies.

Collisional grinding cannot explain the main belt's almost complete attrition. For one, grinding would have damped the fast rotations of the largest asteroids (Farinella *et al.*, 1982). For another, collision evolution models (Bottke *et al.*, 2005) indicate that the largest asteroids ((4) Vesta, (1) Ceres, (2) Pallas, etc.) are undisrupted original bodies; only those smaller than ~100–200 km in diameter follow the prediction for a collisional cascade (Davis *et al.*, 1985). This leaves two categories of ideas: (1) Most of the planetesimals accreted into Moon-to-Mars-sized bodies that consumed nearly all the regional mass. These massive bodies grew fast enough to be ejected from the main belt by mass-dependent processes (Chambers and Wetherill, 1998; Ogihara, *et al.*, 2015). According to this scenario, 100–1000 original planetesimals might have accreted into one lost planet, taking all the mass and leaving behind Vesta and Ceres. (2) Planetesimals were scattered in a mass-independent manner by giant planet migration (e.g. Walsh *et al.*, 2011), quenching their further accretion. In this scenario Vesta and Ceres are the last of a few hundred major bodies that were >99% ejected by resonant scattering.

Each scenario would leave a distinct imprint due to the specific manner of attrition. In the first scenario, Vesta and Ceres are NLBs (Table 2.1) that luckily avoided being accreted by a long-lost planet before it got ejected. They would be among the final almost-accreted remnants of the planet's primary feedstock, and should be hit-and-run survivors according to the simple statistical analysis below. In the second scenario, Vesta and Ceres are lucky in a completely different way: two remaining oligarchs, among the hundred or so largest bodies that accreted between Mars and Jupiter, which were overlooked by the scanning resonances that ejected all their sister planetesimals.

The latter scenario allows Vesta and Ceres to retain their relatively intact compositions (and even excess crust; Clenet *et al.*, 2014), being at the top of the accretion chain. It explains the perplexing diversity of ~200-km asteroids (Psyche, Hygiea, Interamnia, etc.) as survivors of repeated HRCs that were common during the growth of oligarchs.

2.2 Catastrophic Disruption

The complete catastrophic disruption of massive planetesimals is indicated by suites of meteorites (McSween, 1999; Keil *et al.*, 1994), including thousands of iron meteorites that are thought to sample the exhumed cores of ~50–100 differentiated planetesimals (Wood, 1964, Wasson, 1990). Astronomical evidence for disrupted minor planets is less straightforward to interpret, because spectroscopy detects only surface characteristics, and asteroid bulk densities are seldom measured with any precision. A few major asteroids are strongly indicated to be metallic cores, including 16 Psyche, a ~200-km-diameter spheroid, and 216 Kleopatra, a 95 × 220-km "dog-bone"-shaped object, and probably others (compared in Figure 2.1).

Given the apparent frequency with which cores have been exposed and exhumed, the impact disruption of massive planetesimals needs to be effective. But the fact is, the impact kinetic energy per unit mass Q^*_D that is required to destroy a planet, so that the largest final mass M_F is smaller than ½M_1, increases disproportionately with target radius (Benz and Asphaug, 1999; Stewart and Leinhardt, 2012). Planetesimals larger than ~100–200 km in diameter are effectively immune to impact disruption, for expected encounters (Bottke *et al.*, 2005), based on simulations (e.g. Benz and Asphaug, 1999). Evidence for this limit is indicated by the peak in the main-belt differential SFD at ~100–150 km in diameter according to O'Brien and Greenberg (2003) and Bottke *et al.* (2005).