Preface

Starting about twenty years ago, astronomers gradually realized that many of the small bodies in the solar system (asteroids, comets and satellites) are rubble piles, i.e., granular aggregates. The first unequivocal evidence for this came when the comet Shoemaker–Levy nine broke apart, apparently by tides, into dozens of pieces as it passed close to Jupiter. Numerical simulations of self-gravitating granular aggregates were developed and they exhibited such fragmentation during close planetary encounters. Around the same time, researchers recognized that very few asteroids were found with spin periods of less than a few hours, and that this could be understood simply as the consequence of the fragility of fast-spinning bodies to centrifugal breakup. Furthermore, other asteroids and a few close-on satellites of the giant planets were observed in radar "images" and spacecraft images, respectively, to have smooth elongated shapes, suggesting rotational and tidal distortion.

Around the same time, the masses of dozens of asteroids began to be measured, usually by observing the orbital periods of binary asteroids, or by mutual gravitational perturbations of distant asteroids on Mars or another asteroid, or by spacecraft flybys. For those asteroids, comets and a few satellites that had known sizes, their densities were immediately available. More often than not, these measured densities were remarkably low, sometimes less than 0.5 g/cm^3 for comets and small satellites, or often 1–2 g/cm^3 for asteroids and satellites. Because the likely constituents of these bodies (water, ice and rock) have greater densities, the low bulk densities required significant pore space and, accordingly, implied granular aggregates held together primarily by self-gravity, rather than monolithic rocks. Such a loose character is not unexpected for objects that accreted gravitationally in a cold environment.

This book investigates the equilibrium, stability and dynamics of these rubble solar-system bodies. It is clear that any careful investigation will need to consider these bodies as objects with finite extent, and not as mere point masses, and as a granular medium, distinct in its constitutive response from solids and fluids. This book pays particular attention to these aspects.

In this book, we develop a framework for analyzing the dynamics of rotating complex materials; this is predicated on the systematic approximations of the system's kinematics. We apply the method to investigate rotating and self-gravitating granular aggregates in space. Here, we limit the kinematic approximation to, at most, an affine deformation, so that the most general shape that an object can take is that of an ellipsoid. Necessary governing equations may be obtained by a variety of methods, but we prefer to follow the virial method, or volume-averaging, employed by Chandrasekhar (1969). We do this primarily for historical continuity and for greater general familiarity with that method, but also because the current research was motivated to a great extent by Chandrasekhar's treatise that explored similar questions in the context of inviscid fluids.

The constitutive model that we employ depends on the situation. For example, when considering equilibrium, or its stability, the granular aggregate is modeled as a rigid-perfectly-plastic material obeying a pressure-dependent yield criterion, e.g., the Drucker–Prager yield criterion, and deforming post-yield as per an appropriate flow rule. However, when studying the disruptive effects of a tidal flyby, the aggregate is taken to be an ensemble of dissipative spheres whose macroscopic behavior is determined through an application of kinetic theory. The current framework has the advantage that it allows us to improve the kinematic approximation in a structured manner as well as to explore a wide variety of constitutive laws.

The book is divided into four parts. The first part introduces the necessary mathematics and continuum mechanics, as well as, describes affine dynamics that forms the basis of all subsequent development. Part II investigates the equilibrium of rubble asteroids, satellites, and binaries, and applies it to known or suspected cases. Equilibrium, here, refers to possible ellipsoidal shapes that a rubble asteroid can take, and to both shape and orbital separation for granular satellites and binaries. In Part III, we develop a linear stability criterion specifically for rotating granular aggregates, which is then applied to the equilibria obtained in Part I. Finally, in Part IV we provide a pair of examples of dynamical evolution. These relate to the disruption and possible re-agglomeration of rubble piles during tidal flybys.

Finally, I confess to some nervousness. It is dangerous to write a book that may be viewed by some as a would-be successor to Chandrasekhar's classic treatise. Followers in the footsteps of giants risk sinking or getting lost. But then, there are worse ways to go.

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Reference

S. Chandrasekhar, *Ellipsoidal Figures of Equilibrium* (Yale Univ. Press, New Haven, CT, 1969)

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