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Long-term Dynamical Behavior of Highly Perturbed
Natural and Artificial Celestial Bodies

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This thesis explores the dynamical evolution of celestial bodies, both natural and artificial, which are strongly perturbed by solar radiation pressure—a non-gravitational force that has played an increasingly important role in celestial mechanics since the early 1900s. The particular focus is on the high area-to-mass ratio (HAMR) space debris discovered in near geosynchronous Earth orbit (GEO) through optical observations in 2004, and on micron-sized circumplanetary dust particles in the outer Saturnian system. The formalism developed can also be applied to—and, indeed, was unquestionably influenced by—the orbital motion of spacecraft about small bodies (asteroids and comets). The chief difficulties which arise in getting an accurate understanding of the motion of such bodies in highly perturbed dynamical environments come, in part, from the nonlinearity of the dynamical system, but more so from the inadequacy of the classical approaches and methods. While modern formulations based on numerical integrations can give "precise" solutions for specific initial conditions, these afford little insight into the nature of the problem or the essential dependence of the perturbed motion on the system parameters.

The predominant perturbations acting on HAMR objects and circumplanetary dust grains are solar radiation pressure, planetary oblateness, and third-body gravitational interactions induced by the Sun and nearby natural satellites. We developed first-order averaged models, based on the Milankovitch formulation of perturbation theory, which govern the long-term evolution of orbits subject to these perturbing forces. The unexpectedly rich results obtained by the use of this vector formalism are due to certain important circumstances in celestial and quantum mechanics which gave rise to its origin and development. An attempt has been made to trace these historical developments and to put them into the perspective of the present.

The averaged equations of motion hold rigorously for all Keplerian orbits with nonzero angular momentum; they are free of the mathematical singularities associated with circular or equatorial orbits. These approximate equations are written in a concise analytical vector form, which allow our results and demonstrations to attain such extraordinary simplicity and clarity. As a first attempt to understand the disturbed motion, we consider separately the first-order effects of each principal perturbation in altering the orbital elements. We establish that each of these problems is integrable (under certain well-justified assumptions), and that they admit either an exact analytical solution or a complete qualitative description. We then explore the complex interplay between gravitational and non-gravitational perturbations, and examine stable "frozen" orbit configurations and resonances which can occur when these forces act in concert.

These results are applied to the study of the dynamics and stability of GEO orbits and to the identification of robust, long-term disposal orbits for geostationary satellites. We further apply these results towards an understanding of the initial albedo dichotomy of Iapetus, Saturn's enigmatic two-faced satellite. As dust is a ubiquitous component of the Solar System, we discuss the application of our averaged model to a number of other planetary systems. We highlight, in particular, the explanatory power of our approach and how it can modify or guide detailed numerical studies. Indeed, analytical and numerical techniques cannot be separated, and a complete, logically ordered picture is obtained only by the application of both methods jointly.