SHAPES AND DYNAMICAL EVOLUTION OF AGGREGATES FORMED BY GRAVITATIONAL ACCRETION OF PARTICLES ONTO EMBEDDED MOONLETS IN SATURN'S RINGS.

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Introduction: Observations by the Cassini spacecraft of the shapes and the densities of Saturn's small satellites near the ring outer edge also show that they were formed by gravitational accretion of particles [1]. Aggregates formed by gravitational accretion are expected to shape into the Hill sphere in the region if accretion takes place near the Roche limit, while they take more spherical shapes in regions sufficiently far from the Roche limit [2,3]. If the bulk density of aggregates is kept constant during their accretional growth, their Hill radii increase at the same rate as the growth of their physical size, so that the ratio of their physical size to their Hill radius is unchanged [4,5]. On the other hand, when porous, low-density particles coexist with dense bodies, particles can gravitationally accrete onto dense bodies even at radial locations where the low-density particles alone cannot form gravitational aggregates [1]. Observations by Cassini show that the Hill radii of the small moons in the outer A ring and those near the ring outer edge are similar to the observed long axes of these satellites, and their densities are very close to the above critical density at the radial location of each satellite. Using local N-body simulations, [1] demonstrated that a Hill-sphere-filling body can be produced by accretion of small porous particles onto a large dense core. They also derived an analytic expression for the final size of a satellite as a function of the distance from the planet, assuming that the radial distance is sufficiently large so that the satellite's Hill sphere completely covers the core. However, the degree of particle accretion onto moonlet cores in the inner parts of Saturn's rings such as the B and C rings has not been studied in detail.

The Cassini spacecraft discovered tiny structures called "propellers" first in the A ring [6,7]. These structures are thought to be created by gravitational interaction between ring particles and unseen embedded moonlets, and their sizes are estimated as tens to thousands of meters. Recently, propellers in the B ring have also been reported [8]. Furthermore, similar structures likely created by boulders have been inferred for the C ring and the Cassini Division [9]. From these observations, the sizes and orbital distributions of these unseen embedded moonlets are obtained, and such information provides us with clues to the evolution of the ring-satellite system. By clarifying the critical radial distance for particle accretion onto moonlet cores and the dependence of the degree of particle accretion on various parameters, we would be able to give constraints on the origin of these moonlets.

The accretion process of small moons may also be related to the dynamical properties of rings at the time of accretion. The fact that the shapes of these satellites approximately match those of their associated Hill sphere suggests that the moonlet cores were surrounded by a number of particles when the small moons were formed. On the other hand, as for the formation of Pan and Atlas, which have equatorial ridges, a two-stage scenario has been proposed: their main bodies whose shapes are similar to their Hill sphere without equatorial ridges were formed when the rings were thick, and then the equatorial ridges were formed through particle accretion after the rings became sufficiently thin [1,10]. However, effects of the vertical thickness of the rings on the shaping of aggregates formed by particle accretion have not been examined in detail, and it is not clear if thick rings are actually necessary to create bodies with shapes similar to the Hill sphere.

Methods: We carry out local N-body simulations and study the process of particle accretion onto large dense cores in Saturn's rings in detail [11]. In the present work, in addition to the case of icy cores studied in [11], we also examine the case of accretion onto silicate cores. The simulation code we use in the present work is based on our previous one that was used for the study of ring viscosity [12,13], and has been modified from the above one to include a large moonlet core in addition to smaller ring particles [5, 11]. We examine the dependence of the degree of particle accretion on the radial distance from Saturn, in order to provide constraints on the origin of small moons that create structures like propellers in the inner part of Saturn's rings such as the B and C rings. We also investigate effects of the vertical thickness of rings on the process of particle accretion.

The core is initially placed at the origin at rest in the rotating coordinate system. However, particles accrete onto the core, and mass shedding from the aggregate occurs in the sub- and anti-Saturn directions asymmetrically. This changes the core's orbital angular momentum significantly and causes its radial drift [14] especially in the case of the outer part of the rings, which may be related to the observed non-Keplerian motion of propeller moons [15]. In order to simulate such behavior accurately, we also integrate the equations of motion for the core. Then, we carry out coordinate transformation each time step so that the guiding center of the core always stays at the center of the cell. This allows us to track the radial migration of aggregates in the course of particle accretion [11].

Results: First, we examined the dependence of particle accretion on the radial distance from Saturn. We found that gravitational accretion of particles onto moonlet cores is unlikely to occur in the C ring and probably difficult in the inner B ring as well provided that the cores are rigid water ice [11]. However, if silicate cores exist, the above critical radial distance shifts inward to the inner C ring.

Next, we examined the dependence of aggregate shapes on the vertical thickness of the rings. Dependence of particle accretion on ring thickness changes when the radial distance from the planet and/or the density of particles is varied: the former determines the size of the core's Hill radius relative to its physical size, while the latter changes the effect of self-gravity of accreted particles. In the case where a core with density of water ice is placed at the radial location corresponding to the mid-A ring, we found that particle accretion onto high-latitude regions of the core surface can occur even if the rings' vertical thickness is much smaller than the core radius, thus the dependence of the shape of aggregates on ring thickness is rather weak (Figure 1). However, redistribution of particles onto the high-latitude regions is not perfectly efficient in outer regions of the rings such as the outer A ring, where the size of the core's Hill sphere in the vertical direction is significantly larger than the core's physical radius. As a result, aggregates tend to have somewhat flatter shapes with increasing distance from the planet (Figure 2).

Our results suggest that large boulders recently inferred from observations of transparent holes in the C ring were not formed locally by gravitational accretion unless silicate cores exist there, while propeller moonlets in the A ring would be gravitational aggregates formed by particle accretion onto icy or silicate cores [11]. Our results also imply that the main bodies of small satellites near the outer edge of Saturn's rings may have been formed in rather thin rings. We also find that radial shifts can be significant for aggregates embedded in dense regions of the outer part of Saturn's rings such as the A ring, where large particle clumps likely accrete onto and escape from embedded aggregates repeatedly.

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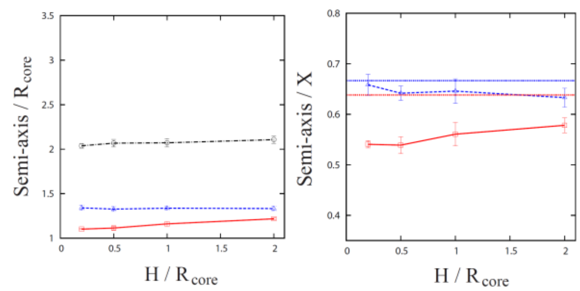

Figure 1: Dependence of axis-ratios of aggregates on H/R_{core} (the ratio of ring thickness to the core radius). The dentities of the core and particles are 0.9 and 0.5 gcm^{-3}, respectively, and the ring's unperturbed optical depth is 0.1. **Left:** Ratios of semi-axes to the core radius. From top to bottom, semi-axes in the radial direction (*X*; black), in the direction of orbital motion (*Y*; blue), and in the vertical direction (*Z*; red). **Right**: The ratios *Y/X* (blue) and *Z/X* (red). The horizontal lines show the analytic values for the Hill sphere [11].

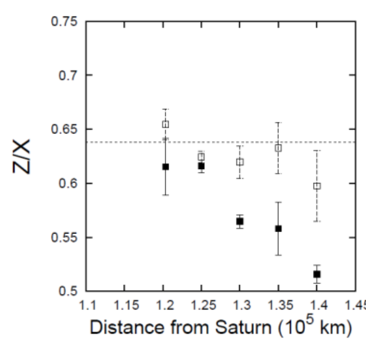

Figure 2: *Z/X* as a function of the radial distance from Saturn. The open and solid symbols represent the case for H/R_{core} = 2 (thick rings) and 0.2 (thin rings), respectively. The horizontal line shows the analytic value for the Hill sphere [11].