Evolution of Planetary Ringmoon Systems

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Abstract. The last few decades have seen an avalanche of observations of planetary ring systems, both from spacecraft and from Earth. Meanwhile, we have seen steady progress in our understanding of these systems as our intuition (and our computers) catch up with the myriad ways in which gravity, fluid and statistical mechanics, and electromagnetism can combine to shape the distribution of the submicron-to-several-meter size particles which comprise ring systems [1-5]. The now-complete reconnaissance of the gas giant planets by spacecraft has revealed that ring systems are invariably found in association with families of regular satellites, and there is an emerging perspective that they are not only physically but causally linked. There is also mounting evidence that many features or aspects of all planetary ring systems, if not the ring systems themselves, are considerably younger than the solar system.

Key words: Planetary Rings, Outer Planets, Origin and Evolution

1. Origin and Evolution

The fundamental goals of ring studies are to understand the origin of ring systems, and to use them as dynamical analogs of astrophysical particle disks in general. The origin of rings has challenged theorists for two centuries; in essence, explanations all relate to the effects of planetary tidal forces. However, consensus has shifted repeatedly over the years between the idea that rings come from moons which were torn asunder by the planet's gravity or by impact (dating from Roche), and the idea that rings are primordial remnants unable to accrete within the zone where tidal forces overwhelm the self gravity of growing satellites [6]. Current understanding favors the "destruction" model in which rings are derivative. In either case, to understand ring origin we must peer back through the evolutionary processes that have acted on the rings and their associated ringmoons to bring them to their current state. We seek evidence of the nature of these processes in the current structure of the rings. A basic property of rings is their "optical depth" \( \tau \), which measures the extinction of radiation by material in the rings (see [1-5]). Large optical depths may be regarded either as the approximate number of times a photon would encounter a particle while passing normally through the ring; small optical depths approximate the fractional area filled by particles, or the probability a photon would encounter a particle.

2. Important processes

Of course, rings are merely an ensemble of individual objects in orbit about their parent planet. Acting on this ensemble are the handful of processes which, in our current understanding, have the major influence on ring structure.

2.1. Viscosity

Collisions between ring particles occur on time scales from small fractions of an orbit to many years, depending on the local optical depth of the rings. The orbiting particles attain random relative velocities due to a combination of physical collisions with their (differentially orbiting) neighbors and gravitational scatterings by the largest members. These random velocities act in a statistical mechanical sense to provide a viscosity $\nu$; in fact, much of ring structure has been studied in terms of the behavior of a viscous fluid. In principle, reliable estimates of ring viscosity could constrain the physical nature of individual particles (compact ice balls or fluffy, easily fragmented temporary agglomerations of debris) and the variation throughout the rings of the balance between forcing and damping processes. However, even the physical behavior of the viscosity is not yet fully understood. “Particle in a box” statistical mechanics is not completely valid in these systems, due to the coupling of the velocity of a particle (and thus its “random” relative velocity at the point of collision with a neighboring particle) and its position in its orbit. Furthermore, theoretical studies have suggested that, as the particle number density increases, the collective properties of the ring particles can resemble those of a liquid more than those of a gas, and ultimately even “solid” phases may “freeze out” at least in transient regions [7]. Some evidence for this may be found in discrepancies being seen in careful radiative transfer modeling of the rings. Their photometric properties in many cases deviate from those of a layer of low volume density, as if the particles in some regions are more closely packed than in others [8]. Only very recently are the many simplifying assumptions which have characterized these studies being relaxed [9], and realistic collisions, particle size distributions, and gravitational scatterings by the larger particles included. Nevertheless, detailed inferences as to particle properties, energy budgets, and ultimately timescales in the real rings from such a perspective remain elusive. Further background on this general subject may be found in [10].

2.2. Gravitational forces

Long before the Voyager encounters, it was realized that the relatively tiny gravitational forces of both nearby and remote satellites, with fractional mass $\mu \sim 10^{-8}$ that of the planet (or even less), could lead to significant effects at resonance locations where the orbital frequencies of the satellite and the ring particles are commensurate (integer fractions or multiples) to a precision on the order of $\mu^{1/2}$ (the “width” of the resonance). Initial studies of individual resonances borrowed