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Physics of planetary rings

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It is difficult to enumerate all the surprises presented by the planetary rings. The Saturnian rings are stratified into thousands of ringlets and the Uranian rings are compressed into narrow streams, which for some reason or other differ from circular orbits like the wheel of an old bicycle. The edge of the rings is jagged and the rings themselves are pegged down under the gravitational pressure of the satellites, bending like a ship's wake. There are spiral waves, elliptical rings, strange interlacing of narrow ringlets, and to cap it all one has observed in the Neptunian ring system three dense, bright arcs – like bunches of sausages on a transparent string. For celestial mechanics this is a spectacle as unnatural as a bear's tooth in the necklace of the English queen.

In the dynamics of planetary rings the physics of collective interaction was supplemented by taking collisions between particles into account. One was led to study a kinetic equation with a rather complex collision integral – because the collisions are inelastic – which later on made it possible, both by using the Chapman-Enskog method and by using the solution of the kinetic equation for a plasma in a magnetic field, to reduce it to a closed set of (hydrodynamical) moment equations [1].

The hydrodynamical instabilities lead to the growth of short-wavelength waves and large-scale structures of the Saturnian rings [1]. We have shown that the formation of the existing dense Uranian rings is connected with the capture of positively drifting ring particles in inner Lindblad resonances which arrest this drift [1]. After the formation of dense rings at the positions of satellite resonances the collective interaction between resonant particles is amplified and the rings can leave the resonance and drift away from the planet and the parent resonance. We can expect in the C ring an appreciable positive ballistic particle drift caused by the erosion of the B ring by micrometeorites. It is therefore natural to assume that the mechanism for the formation of the narrow Saturnian and Uranian rings is the same and that the elliptical Titan, Maxwell and Huygens ringlets are direct relations of the Uranian rings.

A reliable theory of the planetary rings would enable us to consider from completely different perspective the evolution of other cosmic disk systems: protosatellite disks [2], zodiacal and protoplanetary disks [3-5]. In this review we also discuss numerical models of the 3D structure and infrared emission of circumstellar dust disks, incorporating all relevant physical processes. We review the resonant structures of a dusty disk induced by the presence of planets [3-5]. It is shown that the planet, via resonances and gravitational scattering, produces an asymmetric resonant dust belt with one or more clumps intermittent with one or a few off-center cavities. These features can serve as indicators of a planet embedded in the circumstellar dust disk and, moreover, can be used to determine its major orbital parameters and even the mass of the planet.

The results of our study reveal a remarkable similarity with various types of highly asymmetric circumstellar disks observed with the James Clerk Maxwell Telescope and other telescopes around Epsilon Eridani and Vega. The proposed interpretation of the clumps in those disks as being resonant patterns is testable - it predicts the asymmetric design around the star to revolve by $\sim$ 1 deg/yr about Vega and 0.6-0.8 deg/yr about Epsilon Eri. Our simulations indicate that Vega may have a massive planet $\sim$ 2 Jupiter mass at a distance $\sim$ 80-100 AU [3,5], and Epsilon Eri may have a less massive planet $\sim$ 0.2 Jovian mass as a distance of 55-60 AU [3].

Dynamical model of the origin of the warping of the Beta Pictoris disk includes the gravitational influence of a planet with a mass of about 10 masses of Earth, at a distance of 70 AU, and a small inclination (2.5 deg) of the planetary orbit to the main dust disk. The optical image from the Hubble Space Telescope (STIS, observation of team by Sara Heap, our co-author) and results of our simulation of scattered light from warped disk will be compared [4]. The direct signatures of this planet were discovered on 2002 by Keck telescope observations.

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