Saturn's largest ring

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Most planetary rings in the Solar System lie within a few radii of their host body, because at these distances gravitational accelerations inhibit satellite formation. The best known exceptions are Jupiter’s gossamer rings1 and Saturn’s E ring, broad sheets of dust that extend outward until they fade from view at five to ten planetary radii. Source satellites continuously supply the dust, which is subsequently lost in collisions or by radial transport. Here we report that Saturn has an enormous ring associated with its outer moon Phoebe, extending from at least 128 Rs to 207 Rs (Saturn’s radius Rs is 60,330 km). The ring’s vertical thickness of 40 Rs matches the range of vertical motion of Phoebe along its orbit. Dynamical considerations argue that these ring particles span the Saturnian system from the main rings to the edges of interplanetary space. The ring’s normal optical depth of ~2 × 10^{-8} is comparable to that of Jupiter’s faintest gossamer ring, although its particle number density is several hundred times smaller. Repeated impacts on Phoebe, from the faintest gossamer ring, although its particle number density is of micrometres in size and it induces strong oscillations in orbital

By far the largest of Saturn’s distant satellites, Phoebe (mean radius 107 km; ref. 4) is probably the primary source of ejected debris in the outer Saturnian system. The moon follows an elliptical (e = 0.16) orbit around Saturn at an average distance of a = 215 Rs. Phoebe’s orbital plane is tilted by 5° from Saturn’s, but because the moon travels in the direction opposite to that of the inner satellites its orbital inclination is i = 175°. Particles launched from Phoebe share this tilt, and their orbital planes will precess with a characteristic time of thousands of years, producing a vertically extended torus with a full thickness of 2h = 2a(1 + e)sin(i) = 41 Rs, a close match to the observed ring thickness (Fig. 3).

We have conducted numerical simulations of the evolution of different-sized dust grains ejected from Phoebe. Solar radiation pressure is the dominant perturbation force acting on particles up to tens of micrometres in size and it induces strong oscillations in orbital eccentricities, efficiently spreading grains radially inward and outward (Fig. 4). Conversely, the 41 Rs ring thickness is almost unaffected by radiation pressure for two reasons: (1) changes to orbital inclinations depend on the product esin(i), which is always small; and (2) the greatest orbital tilts occur only when apocentres are in Saturn’s orbital plane1. In Fig. 3b, the double peak is characteristic of rings supplied by inclined satellites1, and the more distant ramps of the distribution are most probably due to the slight tilt of the ring relative to Spitzer’s viewing direction.

Figure 1 | Spitzer MIPS imaging in the vicinity of Saturn. The Phoebe ring appears as a bright emission feature centred in mosaics produced from scans at 24 μm (MIPSON) and at a substantially lower signal-to-noise ratio at 70 μm (MIPSON 70). At the closest point to Saturn, the edges of the MIPS 70 image span radii from 128 Rs to 180 Rs. The ring also appears serendipitously in the background of photometric observations of regions near outer satellites Kiviuq and Tarvos (centred at 153 Rs and 190 Rs, respectively; Spitzer Program 03582, principal investigator T. Grav). A photometric observation of Phoebe (Spitzer Program 00071, principal investigator J. Houck) shows little diffuse emission, but the exposure was three times shorter and the ring brightness should be somewhat smaller at 220 Rs. No evidence for the ring appears in additional MIPS 24 μm scans centred at 400 Rs (MIPSOFF). The ring is overwhelmed by scattered light in 24 μm scans (IAPETUS East and IAPETUS West) centred at 44 Rs from Saturn. Two off-target observations (Kiviuq ‘off’ and Phoebe ‘off’) illustrate typical background features in the absence of ring flux. The glints are artefacts that we describe in Fig. 2. See Supplementary Information for further observational details.
These dynamical arguments allow us to calculate key ring parameters. Assuming a line of sight 500\(R_S\) through the ring at the point of observation, the cross-sectional area of all particles in a ring 300\(R_S\) in radius and 40\(R_S\) thick is \(\sim 1.6 \times 10^7\) km\(^2\) (\(\sim 500\) times Phoebe’s cross-section). These numbers depend only weakly on the ring’s unknown particle size distribution; here we have assumed that 10\(\mu\)m grains, the smallest that do not quickly reach Iapetus’ orbit (Fig. 4), are predominant. A ring composed entirely of 10\(\mu\)m grains would have number density \(\sim 20\) km\(^{-3}\) and mass \(\sim 3 \times 10^{11}\) kg, enough to fill a 1-km-diameter crater on Phoebe. In reality, collisions create a size distribution of ejecta, so the number density is likely to be appreciably lower and the ring mass correspondingly higher.

On long timescales, collisions and inward transport become important. Collision with Phoebe, the dominant loss mechanism for particles larger than several centimetres in size, takes on the order of 10\(^{10}\) years. Re-radiation of absorbed sunlight exerts an asymmetric drag force on dust grains, causing them to spiral in towards Saturn with a characteristic timescale of 1.5 \times 10^7\(r_g\) years where \(r_g\) is the particle radius in micrometres. This force brings all centimetre-sized and smaller material to Iapetus and Titan unless mutual particle collisions occur first. The rate of mutual collisions depends on the size distribution of the ring particles and optical depth; if the ring were comprised entirely of 10\(\mu\)m grains, then the collisional timescale would be tens of millions of years, which is comparable to the inward drag timescale. Most material from 10\(\mu\)m to centimetres in size ultimately hits Iapetus, with smaller percentages striking Hyperion and Titan.

Many studies have suggested that dark material migrating inward from Phoebe and other outer Saturnian satellites coated the leading hemisphere of Iapetus\(^5,6,9-11\). Recent observations by the Cassini spacecraft have revealed near-infrared spectral similarities between Phoebe and dark material on Iapetus and Hyperion\(^12,13\), suggesting a common origin for dark material on the surfaces of all three. Dynamical studies predict that small irregular saturnian satellites have struck Phoebe several times over the age of the Solar System\(^4\), providing known historic sources of material, much of which remains in the ring today. The amount of dusty material currently in the ring is enough to cover the dark half of Iapetus to an average depth of 70\(\mu\)m. Interestingly, a ring composed of particles larger than our nominal 10\(\mu\)m grains would be more massive, but would deliver that mass to Iapetus more slowly. As a result, the accumulation rate is relatively insensitive to the ring’s unknown particle-size distribution. Assuming (1) that Iapetus intercepts all this material and (2) that the ring population is currently near its long-term average, the accumulation rate is about 40 \(\mu\)Myr\(^{-1}\). Over the age of the Solar System, deposition at this rate would bury the
leading side of Iapetus to a depth of 20 cm. The population of distant satellites, however, was probably much higher in the past14, leading to more collisions, more debris and a cumulative thickness of material deposited on Iapetus that is probably measured in metres.

The closest analogues to the Phoebe ring are the two gossamer rings associated with Jupiter’s inner satellites Thebe and Amalthea1. These inner moons, while similar in size to Phoebe, are far more prolific sources of debris owing to more energetic collisions near Jupiter. Debris from Thebe re-impacts very rapidly (two thousand years) and so, ironically, the Phoebe and Thebe rings, which differ in scale by a factor of ~100, actually have similar normal optical depths of ~10^{-8}. The new Saturnian structure is many hundred times thicker than the Jovian gossamer rings and its particle number density is correspondingly smaller. Its estimated mass in dust is many thousand times larger than that of either gossamer ring, especially when one accounts for the smaller particles in those rings15. In addition, Phoebe ring particles form a structure symmetric about Saturn’s orbit plane, unlike all other known rings, which are equatorial. Finally, like Phoebe, these particles almost certainly follow retrograde orbits, moving clockwise when viewed from above, rather than counter-clockwise as do classical moons and rings. Although these exotic properties as well as its sheer size make the Phoebe ring unique among known planetary rings, similar structures should also adorn the other gas giant planets.

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