LETTERS

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 rings[1] 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 128R_S to 207R_S (Saturn's radius R_S is 60,330 km). The ring's vertical thickness of 40R_S 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 $\sim 2 \times 10^{-8}$ 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 both interplanetary and circumplanetary particle populations, probably keep the ring populated with material. Ring particles smaller than centimetres in size slowly migrate inward[2,3] and many of them ultimately strike the dark leading face of Iapetus.

In February 2009 we used the Spitzer Space Telescope's Multiband Imaging Photometer (MIPS) to scan regions near Phoebe's orbit to search for a broad debris ring. Mosaics produced from these mid-infrared images at 24 μm and 70 μm (MIPSON in Fig. 1) show a diffuse double-peaked band of light coincident with Saturn's ecliptic plane. The band is not produced by scattered light from Saturn (Fig. 2 and Supplementary Information) and has several characteristics consistent with grains that have spread into a ring after being liberated from Phoebe. The observed peak intensity of the ring at 24 μm is 0.4 MJy sr^{-1}, about 1% of the zodiacal background. Particles with albedo 0.2 and emissivity 0.8 will have equilibrium temperature 85 K near Saturn, and a solid wall of them would emit with intensity 2×10^6 MJy sr^{-1} at 24 μm. The filling factor or line-of-sight optical depth of the ring is then simply the ratio of these two intensities: 2×10^{-7}. The optical depth would be an order of magnitude greater for bright icy grains at 70 K.

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 $a = 215R_S$. 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 $2h = 2a(1 + e)\sin(i) = 41R_S$, 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)[5]. Conversely, the 41R_S ring thickness is almost unaffected by radiation pressure for two reasons: (1) changes to orbital inclinations depend on the product $e\sin(i)$, which is always small; and (2) the greatest orbital tilts occur only when apocentres are in Saturn's orbital plane[5]. In Fig. 3b, the double peak is characteristic of rings supplied by inclined satellites[1], 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.

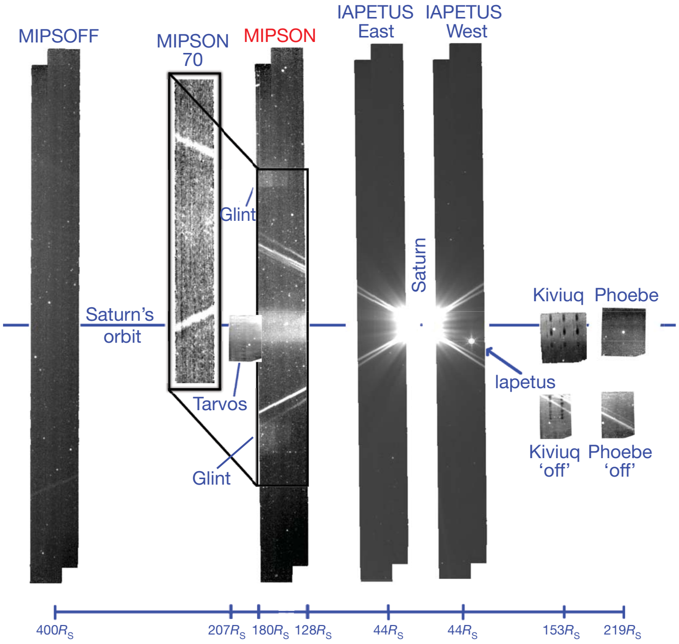

Figure 1 | Spitzer MIPS imaging in the vicinity of Saturn. The Phoebe ring appears as a bright emission feature centred in mosaics produced from scans at 24 μm (MIPSON) and at a substantially lower signal-to-noise ratio at 70 μm (MIPSON 70). At the closest point to Saturn, the edges of the MIPSON mosaic span radii from 128R_S to 180R_S. The ring also appears serendipitously in the background of photometric observations of regions near outer satellites Kiviuq and Tarvos (centred at 153R_S and 190R_S, 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 220R_S. No evidence for the ring appears in additional MIPS 24 μm scans centred at 400R_S (MIPSOFF). The ring is overwhelmed by scattered light in 24 μm scans (IAPETUS East and IAPETUS West) centred 44R_S 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.

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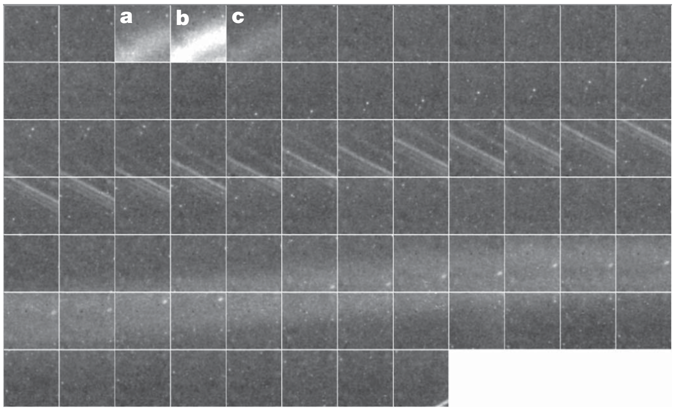

Figure 2 | A subset of the Spitzer MIPS 24 μm Basic Calibrated Data images, comprising a MIPSON scan. As a steadily scanning system, MIPS acquires a series of successive overlapping frames (in sequence from left to right) in which glints (Fig. 1) caused by scattered light appear and fade (**a**–**c**) over the course of a few frames and do not occupy a fixed location on the sky. These glints change geometry and brightness from frame to frame, as expected from a bright out-of-field source reflecting off different portions of the optical system. By contrast, the ring emission near Saturn's orbit plane (bottom panels) appears steady at constant flux and fixed on the sky in multiple MIPS frames.

These dynamical arguments allow us to calculate key ring parameters. Assuming a line of sight $500R_S$ through the ring at the point of observation, the cross-sectional area of all particles in a ring $300R_S$ in radius and $40R_S$ thick is $\sim 1.6 \times 10^7$ km^2 (~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 μm grains, the smallest that do not quickly reach Iapetus' orbit (Fig. 4), are predominant. A ring composed entirely of 10 μm grains would have number density ~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 force on dust grains, causing them to spiral in towards Saturn with a characteristic timescale of $1.5 \times 10^5 r_g$ 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 μm grains, then the collisional timescale would be tens of millions of years, which is comparable to the inward drag timescale. Most material from 10 μm to centimetres in size ultimately hits Iapetus, with smaller percentages striking Hyperion and Titan[3].

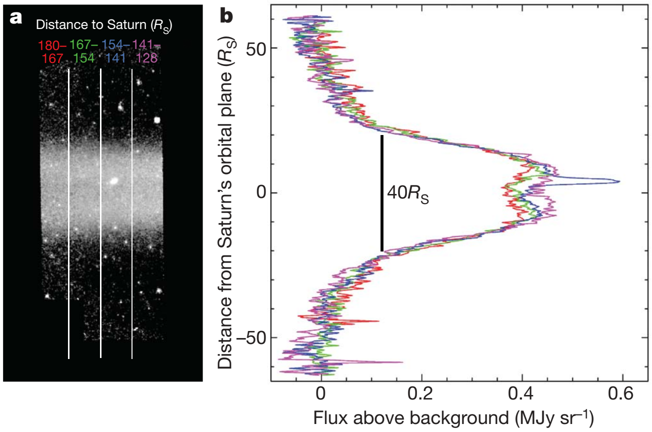

Figure 3 | Vertical profiles through the Phoebe dust structure. **a**, Colours denote radial ranges: magenta, 128–141R_S; blue, 141–154R_S; green, 154–167R_S; and red, 167–180R_S. **b**, The observed flux (MJy sr^{-1}) in four sets of forty averaged columns above and below Saturn's orbital plane produces a broad double peak 0.4 MJy sr^{-1} above the background, with a characteristic width of $40R_S$. The large spike near the peak of the blue profile is produced by the bright background galaxy readily visible in the MIPSON scan (**a**). The separation of the two peaks increases with radial distance from Saturn (**b**), as expected for a distribution of particle orbits with similar inclinations.

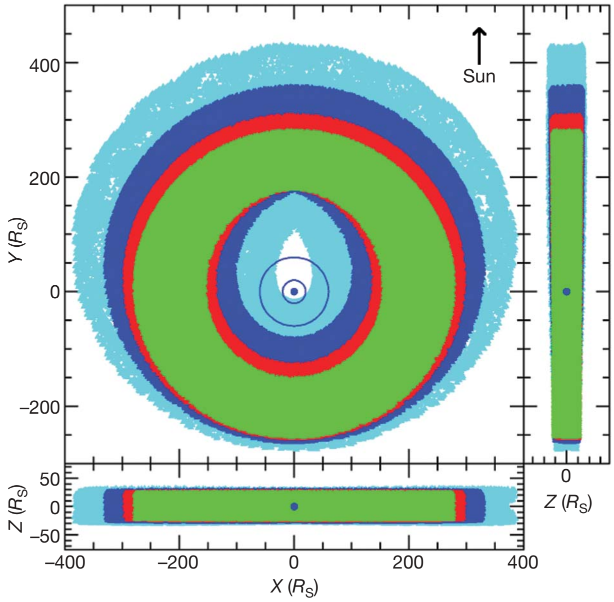

Figure 4 | The orbital distribution of dust grains launched from Phoebe followed for 2,000 years. Colours indicate particle radii in micrometres: 5 (cyan), 10 (blue), 20 (red), and 40 (green). The reference frame is centred on Saturn (blue dot) and rotates with the Sun's average angular motion. The X–Y plane is Saturn's orbital plane, and the Sun is located along the positive Y axis. Circles at $20R_S$ and $60R_S$ denote the orbits of Titan and Iapetus, respectively. Spitzer's view is approximately from the Sun and corresponds most closely to the X–Z plot. The numerical integrations assume a density of 1.6 g cm^{-3}, similar to that of Phoebe itself[4], and include the gravity of Saturn, the Sun, Titan and Iapetus. To apply this figure to other assumed particle densities ρ, simply multiply all particle sizes by $1.6\rho^{-1}$. Solar radiation pressure, the dominant perturbation for small particles, forces the distribution of small grains to be azimuthally asymmetric and offset towards the Sun[16]. Conversely, grains 40 μm and larger form a symmetric torus around Saturn. Within 15 years (half a Saturn orbit), particles smaller than 3.5 μm will strike Saturn or its rings, while those smaller than 1.5 μm will be rapidly ejected from the Saturnian system.

Many studies have suggested that dark material migrating inward from Phoebe and other outer Saturnian satellites coated the leading hemisphere of Iapetus[2,3,6–11]. 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[14], 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 μm. Interestingly, a ring composed of particles larger than our nominal 10 μm 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 μm 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 past[14], 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 Amalthea[1]. 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 $\sim 10^{-8}$. 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 rings[15]. 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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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

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