LETTERS

How Prometheus creates structure in Saturn's F ring

Carl D. Murray[1], Carlos Chavez[1], Kevin Beurle[1], Nick Cooper[1], Michael W. Evans[1], Joseph A. Burns[2] & Carolyn C. Porco[3]

Images of Saturn's narrow and contorted F ring returned by the Cassini spacecraft[1] have revealed phenomena not previously detected in any planetary ring system. The perturbing effect of the inner shepherding satellite, Prometheus, seems to introduce channels through the F ring and a 'streamer'—a line of particles that link the ring to the satellite. The detailed mechanism for the formation of these features has been lacking an explanation. Here we show that these phenomena can be understood in terms of a simple gravitational interaction as Prometheus approaches and recedes from the F ring every 14.7 hours. Our numerical models show that as Prometheus recedes from its closest approach to the F ring, it draws out ring material; one orbital period later, this affected region has undergone keplerian shear and is visible as a channel, in excellent agreement with structures seen in the Cassini images. Prometheus' periodic disruption of the F ring will become more pronounced as the two orbits approach their minimum separation in 2009. The model predicts that the appearance of streamers and the associated channels will vary in a regular fashion on a timescale of one orbital period.

As the closer and more massive of the F ring's two shepherding satellites, Prometheus was always the best candidate for being the narrow ring's major perturber[2–4]. At the time of Cassini's Saturn Orbit Insertion (SOI) on 1 July 2004, the minimum distance between Prometheus[5] and the F ring's core[6] was ~500 km. However, the SOI images[1] (Fig. 1a) obtained by the Cassini Imaging Science Subsystem[7] (ISS) confirmed Voyager observations[8] of an F ring with at least two

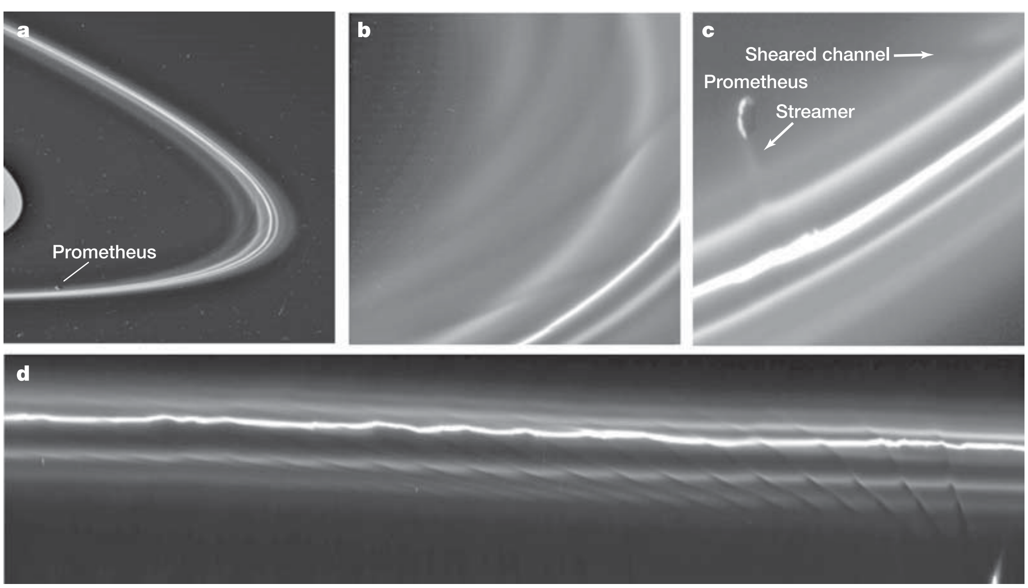

Figure 1 | Cassini images of Saturn's F ring. **a**, Part of an image (W1467350440) of Saturn's F ring taken on 1 July 2004 by the Cassini ISS wide angle camera. The position of Prometheus is indicated. The ring has multiple strands, and the ansa region (at the right) shows 'drape' structure in material that has recently passed Prometheus. **b**, An image (N1467350440) taken by the Cassini ISS narrow angle camera at the same time as **a**, showing the inner part of the F ring near the ansa region. The material interior to the F ring's core (the narrow, bright strand) shows detailed, regular structure with multiple channels giving rise to the 'drape' appearance. **c**, Close-up of a Cassini ISS narrow angle camera image (N1477737741) taken on 29 October 2004 showing Prometheus, the F ring, a streamer of material appearing to connect them and a sheared channel. **d**, A mosaic of 15 reprojected images of the F-ring region taken by the Cassini ISS narrow angle camera on 13 April 2005. The reprojection procedure begins with a raw digital image that has been pointed using background stars. With the assumption that the ring material is in the equatorial plane, the centre of each pixel corresponds to a unique radius and longitude in a standard reference frame. The image covers ~60° in longitude and the radial range is 1,500 km. The slope of the ring strands is a consequence of the eccentricity of the ring becoming evident over the longitude range. The period of time between the first and last images in the mosaic is ~2.5 h. The mosaic shows multiple sheared channels to the left of Prometheus.

[1]Astronomy Unit, Queen Mary, University of London, Mile End Road, London E1 4NS, UK. [2]Department of Astronomy & Department of Theoretical and Applied Mechanics, Cornell University, Space Sciences Building, Ithaca, New York 14853, USA. [3]Cassini Imaging Central Laboratory for Operations, Space Science Institute, 4750 Walnut Street, Suite 205, Boulder, Colorado 80301, USA.

additional strands and a background dust population that extends across $\gtrsim 700$ km in radius. Therefore Prometheus, while not reaching the F ring's core, penetrates the inner dust region each orbital period of Prometheus (14.7 h). A radius versus longitude reprojection of an ISS image taken by the narrow angle camera suggests that the appearance of 'drape' structure[1] (Fig. 1b) resulted from a regular sequence of gap openings or channels in the inner dust sheet, each separated by the spacings of Prometheus' closest approach. If a radial feature were produced at the time and longitude of previous apoapse passages of Prometheus (when the satellite was at its maximum distance from Saturn), then each channel would shear out, producing the sort of gradient that is visible.

Early numerical models of the system[9–11] showed the complicated structures that could result and gave important insight into the dynamics of such encounters, but the existence of 'streamers' had not been suspected on the basis of either the models or the Voyager

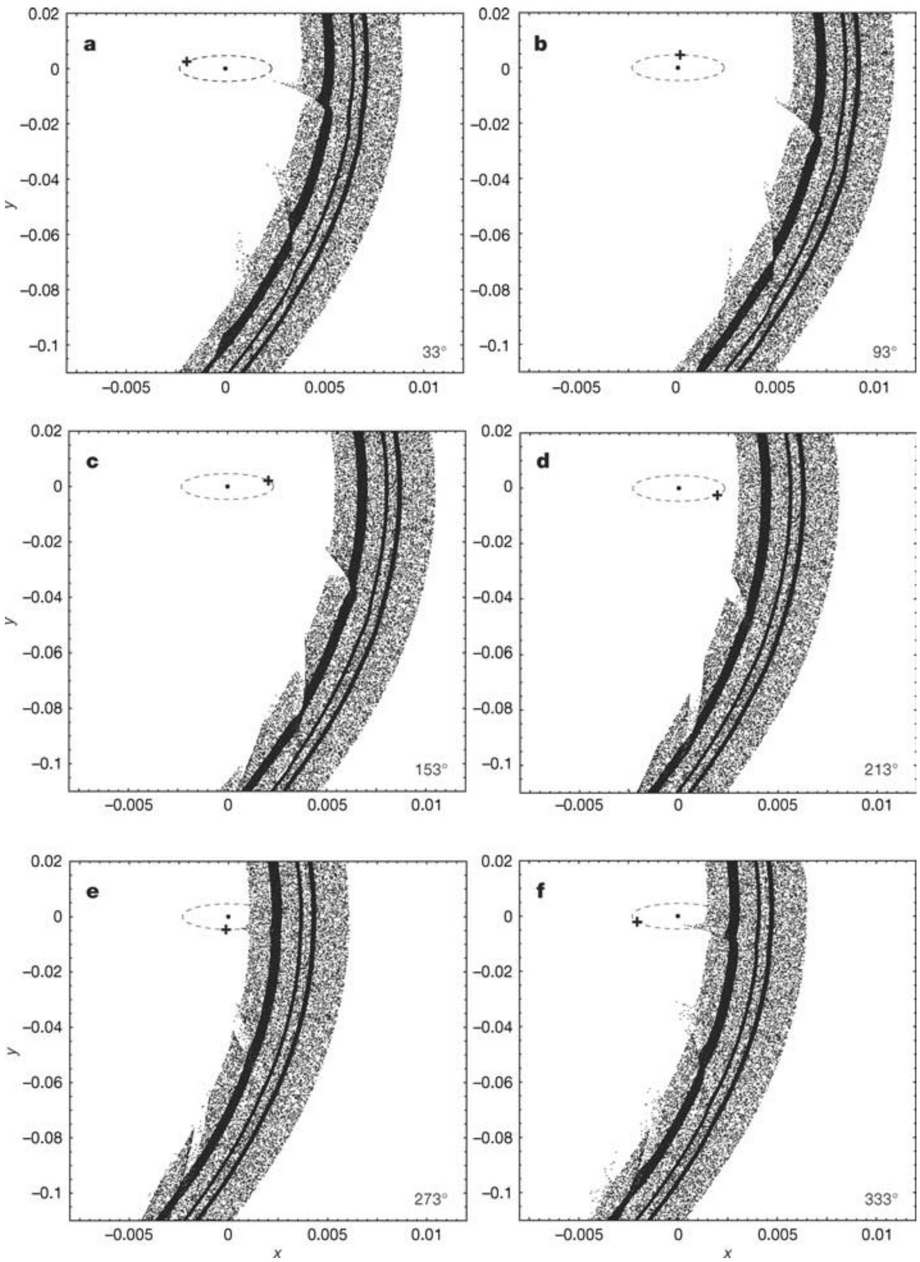

Figure 2 | Numerical modelling of an encounter between Prometheus and the F ring. In each case, the positions of the test particles and Prometheus are plotted in the plane of Prometheus' orbit and in a frame rotating with its mean motion[1,5] (587.285°d^{-1}). All objects are moving in direct orbits (upward or anticlockwise on the figure), but the use of a rotating frame means that the ring particles (all with semimajor axes larger than that of Prometheus) will move more slowly than it and pass from the top to the bottom of each plot. Both the ring ($e = 0.00254$) and the satellite are in eccentric orbits, with Prometheus' apoapse differing from the F ring's periapse by 66.5° corresponding to the configuration at the chosen epoch. The dashed ellipse is the path of Prometheus in this reference frame and the cross (+) in each plot denotes the position of the centre of Prometheus; x points radially outwards from Prometheus while $+y$ is in the direction of overall orbital motion. The plots are for different values of the mean anomaly, M, an angle that increases linearly with time such that $M = 0°$ corresponds to periapse and $M = 180°$ to apoapse. The plots correspond to values of Prometheus' M of 33° (**a**), 93° (**b**), 153° (**c**), 213° (**d**), 273° (**e**) and 333° (**f**). The unit of distance is Prometheus' semimajor axis, and the origin (denoted by a filled circle) is chosen to be Prometheus' centre of epicyclic orbital motion[11] in the rotating frame. Note that the x and y scales are different; this corresponds to viewing the system from an elevation angle of ~9.5° above the ring plane. The different placement of the F ring within each frame is a consequence of the F ring's eccentricity.

images. The realization that Prometheus (orbital semimajor axis, a, 139,700 km; eccentricity, e, 0.0023) could enter parts of the F ring[2,4], combined with improved measurements of the F ring's structure[8], led to a more realistic model[12] that showed streamers even when the long axes of the orbits of Prometheus and the F ring were not anti-aligned. The phenomenon has now been detected in Cassini images[1] (Fig. 1c). We have undertaken a new numerical simulation that makes use of data on the F ring derived from the Cassini images obtained at SOI[1].

The system was modelled with a three-dimensional numerical integration of a spherical Prometheus[13] (radius 50 km, mass 2.11×10^{17} kg) perturbing 200,000 test particles arranged in four radial groups of 50,000 each. The groupings contained three strands with mean semimajor axes of 140,084 km, 140,224 km and 140,314 km with radial widths of 70 km, 20 km and 30 km, respectively. These values were derived from radial measurements made from the ISS narrow angle images[1] obtained at SOI. In addition, we included a 700-km-wide background sheet of particles with a mean semimajor axis and eccentricity equal to that of the F ring. In each group, the particles were assigned random semimajor axes in a uniform distribution across the group's width and random initial orbital longitudes covering 23°. All other initial orbital elements were taken to be those of the F ring[4] at the chosen epoch (Julian date 2453187.71, corresponding to UTC 4:56:25 on 1 July 2004). The range of longitudes was chosen in order that Prometheus would encounter the F ring five times in the course of the integration, thereby allowing us to see the effects on the ring of a series of encounters with Prometheus. Because we were interested in the short-term evolution of the system, we did not include the dynamical effects of Saturn's oblateness. Although the orbits of the strands and Prometheus are all precessing owing to these non-spherical components of the planet's gravity field, their relative precession rate is only $0.057° \mathrm{d}^{-1}$ because of their close proximity. Consequently precessional effects are not important on the ~3-d timescale of our integrations. By considering the strands as being composed of non-interacting test particles, we have also neglected any effects due to collisions between the particles and the self-gravity of the ring. However, by detecting and removing all particles that came within 50 km of the centre of our spherical satellite, we can monitor all collisions between the test particles and Prometheus.

Figure 2 shows six views of the evolved system. In all these plots, the consequences of previous passages of the satellite are clearly visible past Prometheus with distortions in the strands (particularly the inner one) and in the background distribution of particles. The structure in the ring is time-dependent even for those particles that have already encountered the satellite. This happens because, although the particles are no longer being perturbed, we are seeing the outcomes of the velocity kicks that were primarily induced in the various ring particles when the satellite was near its apoapse (mean anomaly, $M = 180°$). Furthermore, the channels in the ring are almost undetectable in Fig. 2a and f but are striking in Fig. 2c and d when Prometheus is near apoapse. As shown in Fig. 4 of ref. 9, the largest kicks in a and e happen to particles that pass Prometheus near its apoapse, but the sign of Δa changes at this point; this means that channels will open in the rings every time Prometheus is near its apoapse.

Figure 2e and f best illustrates the formation of a streamer. The satellite is moving away from apoapse and, as seen in the bump of

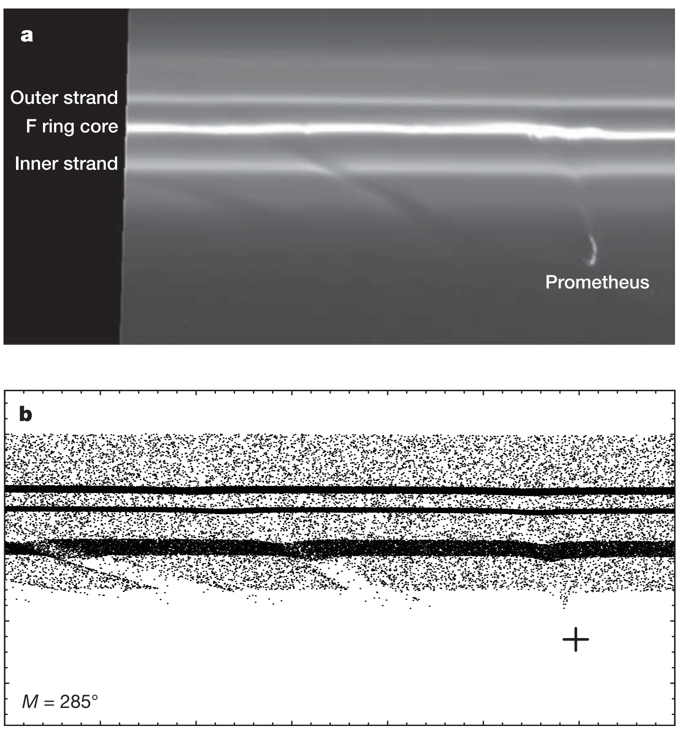

Figure 3 | Comparison between a Cassini image and our model for the same configuration. **a**, A reprojected Cassini image (N1477737741) of the F ring and Prometheus taken on 29 October 2004, and **b**, the corresponding numerical model when the satellite had a mean anomaly of 285° (intermediate between the configurations shown in Fig. 2e and f); the cross (+) denotes the position of Prometheus' centre. In each case the longitude range covers 7° and the radial range 1,500 km. The dark area at the left in **a** was outside the field of view of the ISS narrow angle camera. The existence of a streamer and sheared channels in both image and simulation is clearly evident. In this particular configuration, the model predicts a brightening of each channel on the side furthest from Prometheus, which agrees with the observed structure in the image.

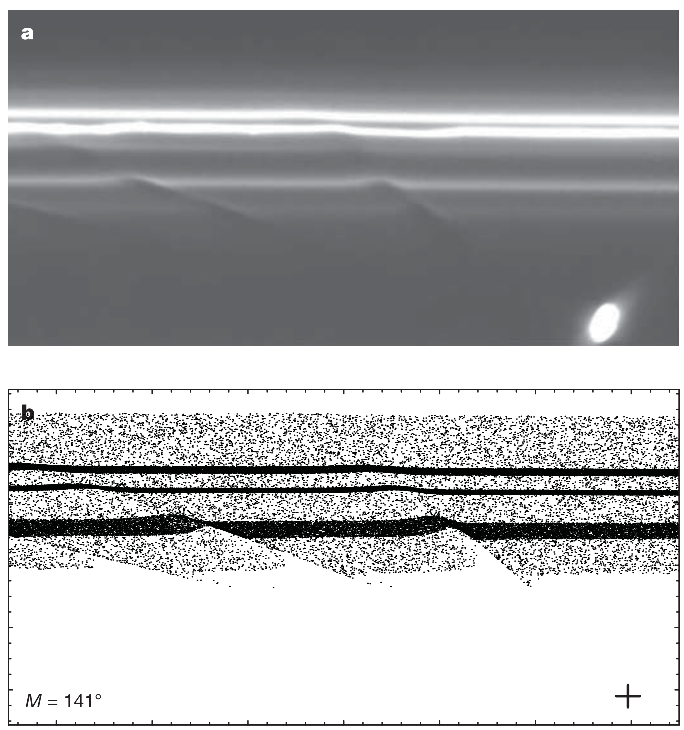

Figure 4 | Another comparison between a Cassini image and our model for the same configuration. **a**, As Fig. 3 but for N1492087204, taken on 13 April 2005, and **b**, as Fig. 3 but for a mean anomaly of 141° (intermediate between the configurations shown in Fig. 2b and c). Longitude range and radial range as Fig. 3. The Cassini image in **a** corresponds to the region at the right of the mosaic in Fig. 1d. There is excellent agreement between theory and observation. Note that the model predicts a brightening on the side of each channel that is closest to Prometheus (the reverse of the situation in Fig. 3), just as observed in the corresponding image.

particles immediately to the right of Prometheus, appears to be dragging particles out of the ring. Our integrations have shown that these particles originate in the innermost strand and background population. Note that the perturbations to create a channel are produced during the same pass but the channel is not fully developed until almost one orbital period later (Fig. 2d). In the meantime, because of the difference in semimajor axis across the ring, differential orbital motion has taken place and the channel has undergone keplerian shear. Note that a channel is not created by particles colliding with the satellite (in the configuration modelled here Prometheus does not enter the F ring), but is due instead to the forced change in orbital elements. However, the satellite's approach does perturb the adjacent particles but the effect is only seen later in the cycle. The integrations show that the particles in the streamer undergo a periodic departure from the ring caused by their forced eccentricity. Their keplerian motion returns them to the ring only for them to reappear periodically later in each cycle.

Figures 3 and 4 show direct comparisons between our model and two Cassini images showing Prometheus near the F ring, including one where a streamer is present. In each case there is excellent agreement, even at the level of the detailed structure on either side of each channel (compare Fig. 1b). It is also worthwhile considering what happens after the ring particles have been perturbed by Prometheus. The particles in a collisionless model continue in unperturbed orbits that are, of course, different from their earlier paths. The image mosaic shown in Fig. 1d confirms this concept. The continual shearing of the channels is evident, and the net result gives a rope-like appearance to the inner strands, reminiscent of features seen in the high-resolution SOI images of the edges of the Encke gap[1]. The wavelength of such structures is $3\pi\,\delta a$, where δa is the difference in semimajor axis between the perturber (Prometheus) and the ring strand[14]. The different lengths between the edges of successive channels (shorter on the edge closer to the satellite versus longer where the channel meets the inner strand) simply reflects the different distance of δa. Figure 1d hints that the gradient along a channel is not constant; this was also detected in the SOI images of the F ring[1] taken by Cassini's Narrow Angle Camera (NAC). One of the predictions of a simplified analytical model[9] of the system is that the size of the change in the orbital elements will be a function of the particle's eccentricity, and so we may be seeing the consequence of different eccentricities in different strands.

Our model is only a first step. It takes no account of collisions between particles or any self-gravity in the ring and yet these processes should be important for the F ring's optically thicker core. Nor does it account for the observed multi-strand nature of the ring[1,8] or the existence of discrete clumps. Nevertheless, it provides a plausible mechanism for the origin of intricate structures detected in the F ring, and suggests that streamers, channels and a variety of other phenomena[1] can all be understood in terms of the simple gravitational effect of a satellite on a ring particle. Our model predicts that the detailed structure of the streamers and channels will vary periodically (while still undergoing keplerian shear) on a timescale of one orbital period, and this can be tested with future Cassini observations. We have also carried out additional simulations, which show that the exact geometry of the streamers is sensitive to the chosen mass of Prometheus and how close it gets to the F ring. Therefore we can use our model and Cassini images to provide an independent method for determining the mass of Prometheus[5,13].

Finally, we note that differential precession caused by Saturn's oblateness is driving Prometheus towards ever-deeper incursions into the F ring with more extreme perturbations, which will culminate in early December 2009 when the apoapse of Prometheus is aligned with the periapse of the F ring. In this configuration we anticipate that Prometheus will suffer impacts from F ring particles and that new structures will be detected in the F ring.

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