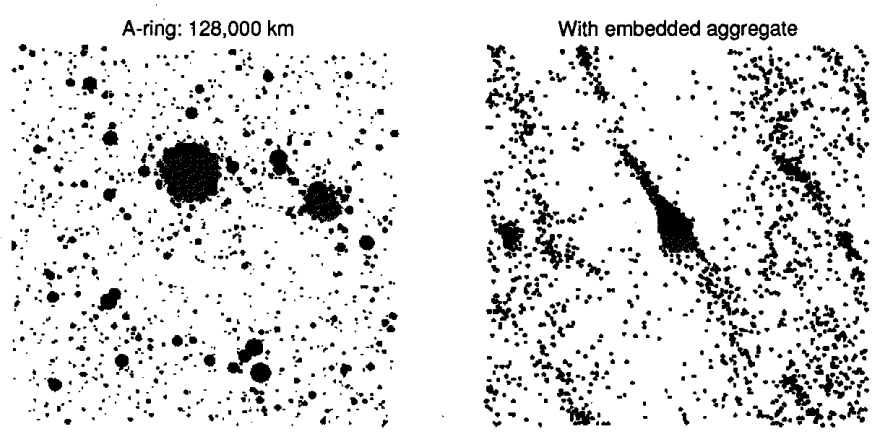

FIG. 2 Simulation model for Saturn's A-ring. The simulation on the left corresponds to Fig. 1, except that $a = 128{,}000$ km and $\Sigma = 480\ \mathrm{kg\ m^{-2}}$, obtained for 1,600 particles. The system is displayed after 10 orbital revolutions, when initial wakes have disappeared and ~30% of the mass has merged into single aggregate. On the right, the formed particle aggregate has been replaced by a single underdense particle with $r = 15$ m and $\rho = 0.3\ \mathrm{g\ cm^{-3}}$, embedded among 1,600 small particles with solid ice density and radius $r = 2$ m (total $\Sigma \approx 450\ \mathrm{kg\ m^{-2}}$). This reduces the computational burden considerably, as most of the CPU time in the previous experiment was spent in calculating the internal collisions among the particles constituting the aggregate. Width of the simulation cell is doubled (340 m) and the figure shows a snapshot of the system after 5 orbital revolutions.

dynamical simulations including cooling[19], where persistent spirals are maintained).

Because so many factors affect the dynamical state of rings, direct particle simulations offer the most reliable method for assessing the gravitational stability and possible presence of gravitational wakes. Figures 1 and 2 show gravitational simulations for three Saturnocentric distances corresponding to the C-, B- and A-rings. The elastic properties of particles follow laboratory measurements[9], and the size distribution is represented by a power law with slope 3, in accordance with Voyager measurements[21]. Although the distribution is truncated at the lower end, both the maximum particle size, which governs the velocity dispersion through gravitational encounters, and the local surface density, governing collective phenomena, should be fairly representative of those in the actual ring system (see ref. 22).

Figure 1 shows no trace of collective phenomena for the C-ring, because of its low surface density and because it is close to the planet. For the B-ring model, clear wakes are present. Inspection of the simulation system at various times shows that although individual wakes are transient phenomena and lose their identity in a few orbital periods, the overall density variations stay at roughly constant. The scale of these wakes seems to be consistent wih the Julian–Toomre estimate, although the pitch angle is about twice that expected for a strictly two-dimensional case, or ~30° instead of 15°. The velocity dispersion is roughly twice that seen in a similar run without self-gravity: for the largest particles the observed σ_r corresponds to $Q_T \approx 2$, and for the smallest, $Q_T \approx 3.5$. When gravity is included, the velocity dispersion shows fluctuations of ~30%, following the formation and disappearance of individual strong wakes.

For A-ring parameters, the behaviour is different. As for the B-ring, the initially cool system forms strong wakes within the first orbital revolution, but these wakes tend to collapse into elongated, almost radial particle groups, which may merge into a single aggregate (Fig. 2; aggregate size ~15 m). This behaviour confirms the proposed[18] rapid formation of aggregates, although it occurs only at the outer portions of the rings. In the case displayed, the aggregate is full of voids, and its final effective density is 30% of that of its constituent particles. Because of the lowered density, additional particles can no longer accumulate at its surface. In several additional runs, including particle spins and friction, and in models including more-elastic impacts, aggregates similar to that of Fig. 2 start forming at $a = 125{,}000$–$130{,}000$ km. Because the number of simulation particles is limited, it is difficult to estimate the actual maximum size possible if new particles were continuously available, and if the mutual collisions between aggregates were also included. Including centimetre-sized particles might also aid further growth as they could increase the mean density of the aggregates by filling the empty spaces between larger particles.

Figure 2 (right) displays another run for the A-ring, where the aggregate of the previous experiment has been treated as a single underdense particle. The size of the calculation cell has been doubled, and the wakes excited by the aggregate become visible. Also evident is the zone partially cleared by the massive particle. Compared with the previous B-ring model or the initial A-ring model, the pitch angle of wakes is reduced, especially at the inner edge of the gap.

These dynamical models are consistent with several observations. For example, the distinctly non-Poisson character of the photon noise in the Voyager stellar occultation measurement (PPS) indicates[6] that for the A-ring, the surface area locally covered by particles deviates significantly between successive measurement points. For the C-ring, uniform density is implied. The extra noise was explained by large maximum particle size, the variance arising from the presence or lack of large particle in each sampling area. According to our experiments, particles with size exceeding 10 m could be identified with the particle aggregates, without any need to revise the cut-off radius of the actual underlying particle distribution. The same explanation was also mentioned in ref. 6.

Dones and Porco[5] (see also Esposito[23]) have shown by light-scattering simulations that Julian–Toomre type wakes can in principle reproduce the observed azimuthal variations in A-ring brightness. Our model of wakes exited by an embedded aggregate (Fig. 2) should therefore be at least qualitatively consistent with the observations. Detailed photometric calculations would be needed to ascertain whether the present model correctly explains the brightness maximum at 165° from the superior conjunction. An unexpected new finding is the predicted wake structure in the B-ring, as no asymmetry has been measured. This could be due to the large optical depth: for example, Franklin and Colombo[24] note that even 10% variations in the surface density would not be detectable for this ring. Another possibility[23] is that the wakes are on a smaller scale than for the A-ring. Possible observational support for B-ring wakes is provided by the PPS measurement: according to Showalter and Nicholson[6], in these regions of B-ring that are not totally opaque, the implied variance is larger than elsewhere in the rings, suggesting structures on a scale of 20 m which would be roughly consistent with the simulated wakes. Dynamical arguments alone strongly suggest that B-ring wakes exist, unless the adopted standard models for $N(r)$, ε, Σ or ρ need serious revision. □

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1. Camichel, H. *Ann. Astrophys.* **21**, 231–242 (1958).
2. Thompson, W. K., Lumme, K., Irwine, W., Baum, W. & Esposito, L. *Icarus* **46**, 187–200 (1981).
3. Colombo, G., Goldreich, P. & Harris, A. W. *Nature* **264**, 344–345 (1978).
4. Franklin, F. A. *et al. Icarus* **69**, 280–296 (1987).
5. Dones, L. & Porco, C. *Bull. Am. astr. Soc.* **21** No. 3, 929 (1989).