Solving the puzzle of Enceladus's active south pole

Francis Nimmo[a,1]

Enceladus is a small moon of Saturn that has active geysers at its south pole. Why this activity is confined to one small region of the surface has been a puzzle for 15 y. Now, in PNAS, Kang and Flierl (1) provide a possible answer: Localization of activity can arise spontaneously via a feedback process in the ice shell. While their model is a highly abstracted version of reality, it may also be applicable elsewhere, including Jupiter's moon Europa and even our own Moon.

The discovery of geysers and excess heat at the south pole of Enceladus was one of the biggest surprises of the Cassini spacecraft mission (2). Because Enceladus is so small, the only plausible source of this energy is tidal heating: Enceladus gets squeezed and stretched by Saturn's gravity as it follows a slightly elliptical path around Saturn. A fundamental characteristic of tidal heating is that it is symmetrical: Both poles are expected to experience the same degree of heating (3). It was therefore very puzzling that the north pole of Enceladus appears ancient and heavily cratered, while the south pole is geologically young, active, and warm.

Further spacecraft investigation revealed that Enceladus consists of an ice shell of variable thickness sitting atop a salty ocean and a low-density rocky core (4). Although the ice shell is only ~6 km thick at the south pole, it is also notably thinned at the north pole (~14 km) compared with the average thickness of ~20 km (4). Since tidal heating is generally greatest at the poles (3), the polar thinning of the ice shell is readily explained. What is not at all obvious is why only the south pole exhibits extreme thinning and active geysers.

Several explanations for this observation have been proposed. One possibility is long-wavelength convection resulting in a single upwelling (5). However, the thin ice shell and large lateral thickness variations are both inconsistent with convection. Another alternative—the "last refuge of the scoundrel"—is to appeal to a giant impact.* Unfortunately, the thermal effects of this impact would probably only last for a few million years, and the probability of such an impact having happened so recently is negligible.

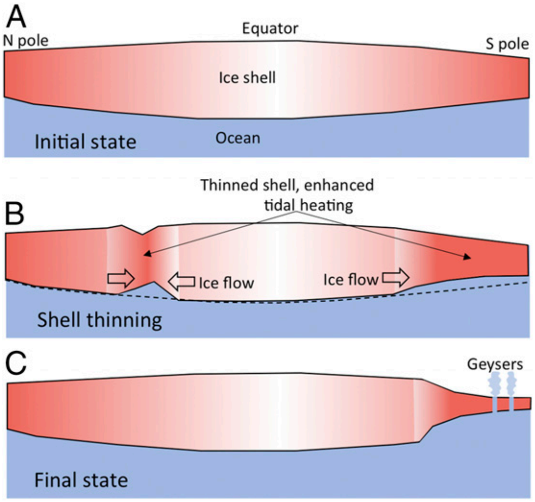

Fig. 1. Schematic development of symmetry breaking at Enceladus. (*A*) The initial tidal heating and ice shell thickness are symmetrical about the equator. (*B*) Regions where the ice begins to thin experience more tidal heating; lateral flow of the ice shell removes narrow thinned areas but not wide ones. (*C*) A wide region of shell thinning runs away and the ice shell fractures.

A significantly more plausible idea is that of Hemingway et al. (6). They argue that progressive freezing of the shell builds up pressure in the ocean and eventually causes the shell to fracture. Because tidal heating is maximized at the poles, the first fracture will occur at one pole. As soon as the fracture occurs, the excess pressure is released, and fracture formation elsewhere is shut off, thereby ensuring that only one pole is active.

Kang and Flierl (1) take a different approach. They show that a combination of two plausible physical effects can lead to a runaway situation in which tidal heating ends up being concentrated at one pole (Fig. 1). The first effect is that local thinning of an ice shell leads to greater total tidal heating there (7); effectively, strain is being progressively focused, somewhat like the development of an aneurysm in an

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[a]Department of Earth and Planetary Sciences, University of California, Santa Cruz, CA 95064

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[1]Email: fnimmo@ucsc.edu.

*J. H. Roberts, A. M. Stickle, K. Craft, American Geophysical Union Fall Meeting, December 12–16, 2016, San Francisco, CA.

inflating balloon. On its own, this effect can cause shell thickness contrasts to run away: Thin areas would get thinner, and vice versa. However, the second effect now intervenes: The warm base of the ice shell can flow and will preferentially remove narrow (short-wavelength) areas of thinned ice (8). The combination of these two effects means that only broad (long-wavelength) areas of thinning can survive. Because tidal heating is highest at the poles, some parameter choices result in a single pole developing a thin shell, a high heat flux, and (by inference) fracturing. This explanation is attractive because it allows small, random perturbations to grow and produce the situation we see today.

Another attractive aspect of the proposed mechanism is that it is generally applicable to satellites with thin shells overlying oceans. The authors suggest the Jovian moon Europa as a possible candidate (1), although Europa does not exhibit the same kind of extreme variations in surface age or activity that Enceladus does (9). A less obvious but perhaps more promising application is to the "magma ocean" phase of the Moon, another body which exhibits long-wavelength shell thickness variations and which experienced intense early tidal heating (10).

A good model makes testable predictions. The Kang and Flierl model is mostly explanatory rather than predictive, and new data from Enceladus will not be acquired any time soon. Nonetheless, one possible test is to see whether the runaway process described in ref. 1 can explain the observation that there are other regions of Enceladus that experienced deformation and high heat fluxes in the past (2). Doing so almost certainly requires some way of resetting the runaway process [and this comment applies to the ocean pressure model (6) as well]. One possible way of doing so would be to appeal to a reorientation of the ice shell with respect to the rotational axis, as may happen for icy satellites (3, 11). Another is to appeal to changes in Enceladus's orbital characteristics, which may experience long-period variations (2).

Despite its attractiveness, there are a few objections to the Kang and Flierl model. The first is simply that the parameter space in which their runaway mechanism can occur is rather narrow. While the values required are permissible, we don't know whether they reflect those of present-day Enceladus or not.

The second objection is that their model is simplified. In many ways this is a virtue—it makes the physical processes at work more transparent—but it carries the risk of missing effects that may be important. For instance, the ability of the ocean to transport core heat upward and to different latitudes (12) may complicate matters. Similarly, melting at the pole could release fresh, buoyant water into the salty ocean beneath; this would tend to divert ocean heat away from the pole and reduce the melting rate. Future studies in which ice shell and ocean processes are dynamically coupled are likely to yield a rich range of possible behaviors.

Finally, it is worth noting that the authors' primary expertise is in atmospheric and ocean dynamics, not planetary science. It may be that it is this fresh perspective that has allowed them to come up with their idea. Conversely, the fact that the study of icy satellites can attract researchers from relatively distant disciplines is an indicator of the health of the field, and a sign that there are still many equally fascinating puzzles to solve.

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