

Explaining the two-toned nature of Iapetus

When Jean-Dominique Cassini discovered Saturn's moon Iapetus in 1671, he was surprised to find it visible on just one side of its orbit around the planet. The moon's orbit had to be synchronous, he correctly inferred, with its leading hemisphere far darker than its trailing one. Some clever Earth-based IR radiometry 300 years later confirmed the extreme albedo difference, and images from the Voyager mission in the early 1980s revealed charcoal dark and frosty bright surfaces that interleave, like two halves of a tennis ball. But the origin of the pattern and sharpness of the dark-bright boundaries remained mysterious.

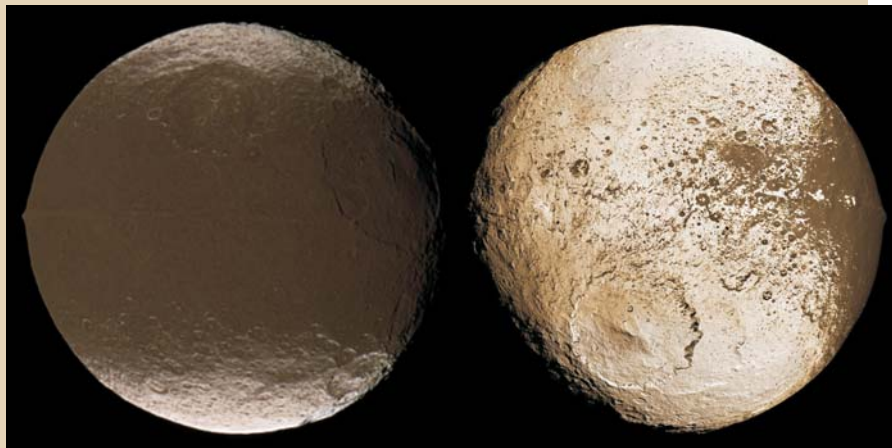
As early as 1974, Asoka Mendis and Ian Axford had proposed a plausible explanation: With its mean density close to that of water, Iapetus is a dirty ice ball. Dust from micrometeorites hitting the leading hemisphere, the pair theorized, might darken it enough to trigger the thermal migration of ice: sublimation from dark, warmer patches centered around the moon's equator and recondensation at bright, colder areas near the poles and on the trailing side. The brief proposal, overlooked by subsequent researchers, lay dormant for 33 years.

Data collected since 2004 by the *Cassini-Huygens* spacecraft offer the most compelling evidence yet for Mendis and Axford's view. In two companion papers, John Spencer of the Southwest Research Institute in Boulder, Colorado, Tilmann Denk of the Free University of Berlin, and their colleagues analyze *Cassini's* visible and IR data of Iapetus's surface and present computer simulations that reproduce the observed albedo pattern and its likely 2.4-billion-year evolution from a modest initial dusting.^{1,2}

Although shades of color are difficult to discern here, visible-spectrum images such as these photographs reveal a material coating Iapetus's leading side that is redder than the dirt presumed intrinsic to the moon there and on its trailing side. The foreign dust is thought to be swept up, like bugs on a windshield, as Iapetus orbits Saturn at 3.3 km/s. That idea gained additional support last year when the University of Virginia's Anne Verbiscer and colleagues, using the *Spitzer Space Telescope*, detected an enormous gossamer ring of particles tracking the retrograde orbit of Saturn's distant moon Phoebe.³ Particles from the ring could spiral into Iapetus at 6.5 km/s, effectively sandblasting its leading side.

Iapetus's piebald appearance at low latitudes on the trailing side is clear evidence for the thermal segregation of ice from dirt.

Thanks to the long exposure to the Sun during Iapetus's slow, 79-day axis rotation, the dark material reaches 129 K, warmer than any surface in the Saturn system except for internally heated fractures on Enceladus, while bright material remains a cooler 113 K. As micrometeorites impact the moon's surface, they "garden" it, churning up material to expose virgin ice crystals that can then sublime and recondense at cold traps elsewhere. Bright areas become brighter and dark areas become darker, probably to a thickness of tens of centimeters over a couple billion years, Spencer estimates.



The process happens both locally and globally. Ice can migrate from warm equator-facing crater walls to cool pole-facing ones, for example, or from one side of the moon to the other, giving rise to its two-faced appearance. Just 1500 km in diameter, Iapetus is small and lacks an atmosphere, which allows water molecules to follow ballistic trajectories up to hundreds of kilometers in range.

Still unresolved is the precise origin of the infalling dust. The dark surface components of Phoebe and Iapetus are both composed of coal-like hydrocarbons and are spectrally similar, but with an important distinction: Phoebe is gray—or, more precisely, neutral, with a flat spectrum in the visible and near-IR—not red. Planetary scientists are now puzzling over what might account for the difference.

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References

1. J. R. Spencer, T. Denk, *Science* (in press), doi:10.1126/science.1177132.
2. T. Denk et al., *Science* (in press), doi:10.1126/science.1177088.
3. A. J. Verbiscer, M. F. Skrutskie, D. P. Hamilton, *Nature* **461**, 1098 (2009).

atom to a Rydberg state $|r\rangle$. The third, applied to the target atom, has no effect because of Rydberg blockade. The fourth returns the control atom to $|1\rangle$, and the fifth, acting on a superposition of states, completes the target atom's journey to $|0\rangle$.

However, if the control atom starts in $|0\rangle$, pulse 2 is of the wrong energy to raise it to $|r\rangle$. So pulse 3 takes the $|1\rangle$ component of the target atom on a round trip to $|r\rangle$ and back and changes its phase, which means that pulse 5 re-

turns the atom to $|1\rangle$ rather than lowering it to $|0\rangle$. Similarly, if the target atom starts in $|0\rangle$, its state is flipped if and only if the control atom starts in $|1\rangle$. The other CNOT gate, shown in figure 1b, is the controlled amplitude swap, or A-S. It accomplishes the same thing using only π pulses.

Applying a CNOT gate when the control atom is in a superposition of states produces an entangled state. For example, when the control atom is in $(|0\rangle + i|1\rangle)/\sqrt{2}$ and the target is in $|0\rangle$, the

CNOT gate yields $(|01\rangle + |10\rangle)/\sqrt{2}$, the same as the Paris researchers produced. Different initial conditions yield other entangled states.

Entangled webs we weave

"The most challenging part," says the Paris group's Browaeys, "was to analyze the amount of entanglement we produced in the experiment." To determine how faithfully their schemes produced the desired entangled state $(|01\rangle + |10\rangle)/\sqrt{2}$, both groups started by