VOL. 106 | NO. 4
APRIL 2025

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level clouds, which trap most infrared radiation in Earth's atmosphere).

2023 saw 1.5% fewer low-level clouds compared to previous years, especially in the Northern Hemisphere. That decrease continues a trend from the previous decade, which saw especially strong declines in low-level clouds over the Atlantic.

> **"Unscrambling the egg is a challenge."**

Why these clouds are disappearing isn't fully known, though it's likely due in part to natural yearly and decadal variations in atmospheric patterns. Some researchers have also argued that a reduction in marine aerosols (associated with regulations limiting shipping emissions) is to blame. Others point to feedbacks from a changing climate.

"Unscrambling the egg is a challenge," said Norman Loeb, a NASA scientist and principal investigator for CERES, who wasn't involved with the research. "Having the correct attribution of what's behind these trends in the energy budget and top of atmosphere radiation, I think that's really important."

If the decrease in low-level clouds comes from more than natural fluctuations, that could mean the influence of feedback effects or marine aerosols on low cloud formation is stronger than currently thought. Both might mean that current climate models are underestimating how much warming will happen in the future, according to Goessling.

Knowing how much warming we're in for is important for designing climate and emissions policies and interventions, so it's crucial to be accurate. As the new study shows, understanding what's happening to the clouds is an important part of that.

"This is kind of crunch time," he said.

Loeb said research into how cloud cover is changing should soon be accelerated. An effort to coordinate new climate models with updated data through 2022 will give the climate science community an easier way to compare results, he said. "We're going to make a lot of progress with this latest set of [data]," Loeb said.

By **Nathaniel Scharping** (@nathanielscharp), Science Writer

Pluto Captured Charon with a Kiss

A composite image of Pluto (foreground) and Charon shows the striking color differences between the two bodies. Credit: NASA/JHUAPL/SwRI

Astronomers have long thought that Charon, the largest moon of Pluto, formed after a collision in the early solar system. New simulations of that encounter have revealed that during a chance meeting in the outer solar system, Charon and Pluto may have become smooshed together in an hours-long "kiss" before settling into a lifelong orbit around each other.

"We were genuinely quite surprised by what we found," said Adeene Denton, a geologist and planetary scientist at Southwest Research Institute in Boulder, Colo., and lead researcher on the study.

That kiss-and-capture process could help settle a long-standing debate about the evolution of the Pluto-Charon system and also explain the evolution of other binary systems beyond Neptune's orbit.

An Unlikely Icy Pairing

In the early years of the solar system's history, chaos reigned, and collisions were common. The history of small impacts is written in the craters that dot the surfaces of bodies from asteroids to planets. Larger impacts left their mark by creating rings, oblong snowmen, and moons—including Earth's.

Even though large collisions used to be common, they did not always result in a pairing. Sometimes two large objects bounced off each other like billiard balls in a so-called hit-and-run collision. Sometimes one object was completely obliterated while the other survived, sometimes the two objects grazed and merged together, and sometimes both objects were partially destroyed but eventually re-formed with one object captured into an orbit around the other.

"The best example that we have for collisional capture of the satellite is the Earth and the Moon," Denton said. Astronomers and planetary scientists have done extensive research into this collision, thanks in large part to centuries of detailed observations of how Earth and the Moon move around each other. In recent decades, lunar samples returned to Earth have shown how the Moon and Earth are geochemically similar, further supporting this theory.

"In the outer solar system, we are not so lucky to have this information," Denton added.

This has presented a challenge to scientists like Denton who have been trying to understand how diminutive Pluto could have survived a similar collisional capture of its largest moon, Charon.

Previous collision simulations have shown that it's exceedingly difficult to form the Pluto-Charon system in the same way that the Earth-Moon system formed.

One reason is Charon's heft: Charon is about 50% the size and 12% the mass of Pluto. Our Moon, on the other hand, is 27% the size and 1.2% the mass of Earth. Charon would have had to travel very slowly or impact at a sharp angle to end up as Pluto's moon—neither scenario is very likely, but astronomers grudgingly accepted that it must have happened that way because it was the only way to make the capture stick.

But Denton realized that past simulations failed to account for the fact that Earth and the Moon are mostly made of rock, whereas Pluto and Charon have a significant amount of ice.

"In the outer solar system, we are not so lucky to have this information."

"If we instead approximate them as geologically realistic bodies made of rock and ice, how does that change the conditions under which Pluto can capture Charon?" Denton asked. The answer, they felt, lies in the material strength of ice compared with rock.

First Came a Kiss, Then Came Marriage

Denton and their colleagues started by incorporating material strength into existing simulations of the Pluto-Charon collision, which were based on the Earth-Moon collision. In the Earth-Moon collision, the speeds and relative masses of the two initial objects meant that once they collided, the debris was entirely molten and behaved like a fluid.

But at the speed and sharp impact angle that had previously been presumed for a Pluto-Charon collision, "the two bodies don't deform as much because they're now behaving like ice and rock would, and not fluid," Denton explained. "Charon would come in and hit Pluto and keep going and leave the system."

When the researchers started exploring other, more typical impact speeds and angles, they found that the material strength of an ice-rock mixture made a big difference. The simulations showed that when proto-Charon struck proto-Pluto, friction within the rock-ice material distributed some of the impact momentum, causing the two objects to become connected for tens of hours—the "kiss." The ice's strength prevented them from fully merging, and eventually, the two objects physically separated but remained in orbit around each other—the "capture."

These results were published in *Nature Geoscience* (bit.ly/Pluto-Charon-kiss).

Explaining Pluto and Its Neighbors

William McKinnon, a planetary geologist at Washington University in St. Louis who was not involved with this research, called the kiss-and-capture mechanism "a variation on a theme" of planetary collisions and added that "the inclusion of strength in the numerical models is an important advance."

The team found that a kiss-and-capture scenario produced enough collisional debris to form Pluto's minor moons (Hydra, Nix, Kerberos, and Styx), though the moons are so small that the simulations would have had to be thousands of times more powerful for them to be seen, Denton said.

Kiss-and-capture could also help resolve an open question about Pluto's temperature. Astronomers think that the planet had an underground liquid ocean for most or all of its history, but where it got the heat to sustain that ocean is unknown. Many models of the solar system's formation suggest that Pluto formed much later than planets in the inner solar system, but if it did, it would have missed out on a lot of radioactive materials that could have heated its interior.

But with a kiss-and-capture, "theoretically, you could add a heat source to Pluto from the impact and then sustain heating of Pluto over time as Charon starts to migrate outwards," Denton said.

However, McKinnon cautioned that Pluto's precollision heat is still an important factor to consider in a kiss-and-capture scenario. A warm proto-Pluto or proto-Charon would have distinctly separate layers of rock and ice, whereas cold objects would have a more even mix of rock and ice throughout. That would affect how much of each material's strength came into play during the collision. It would be tough, he said, to gather convincing evidence for kiss-and-capture versus the more traditional graze-and-merge.

"I suppose that definitive evidence for an ocean today on Pluto would argue for an even warmer Pluto in the past, which would argue against kiss-and-capture," he said.

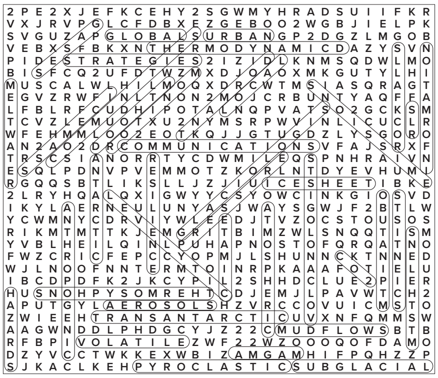
Because a kiss-and-capture depends on the material strength of the colliding objects, it might have happened to other icy objects in the outer solar system. The researchers also simulated the collision of Orcus and Vanth, another pair of co-orbiting icy objects out beyond Neptune's orbit with a mass ratio similar to that of Pluto and Charon. Kiss-and-capture worked for that system, too.

"This process might be something that happens all across the Kuiper Belt, but it might not necessarily be something that's happening, say, in the asteroid belt."

"This process might be something that happens all across the Kuiper Belt, but it might not necessarily be something that's happening, say, in the asteroid belt," Denton said.

The team plans to simulate this kind of collision for other pairs of trans-Neptunian objects like Eris and Dysnomia and Quaoar and Weywot. McKinnon said that seeing kiss-and-capture work for other binary systems in the Kuiper Belt—of which there are many—would help convince him that it happened to Pluto, too.

By **Kimberly M. S. Cartier** (@AstroKimCartier), Staff Writer



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