CORE CONCEPTS

Albedo is a simple concept that plays complicated roles in climate and astronomy

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Dark objects left out in the sun get warm. Lighter-colored objects, not so much. On a planetary scale, this simple, familiar phenomenon—associated with a characteristic called albedo—drives weather and climate. On a regional scale, it can influence the melting of sea ice and glaciers.

And yet, as with many factors influencing climate, albedo's effects are complicated. Changes in Earth's overall albedo, for example, influence the planet's average temperature, which in turn affects the amount of water vapor the atmosphere can hold, which in turn affects our planet's cloudiness—which in turn affects the planet's albedo, starting the cycle anew. Because researchers often have difficulty determining how strong such feedbacks are, it's hard to incorporate them in climate models.

But this seemingly simple concept extends beyond scrutiny of Earth to the study of other heavenly bodies.

For decades, albedo has helped astronomers assess our planet's risk of damage from rogue asteroids by offering a means of estimating their sizes. In the future, albedo could even help astronomers identify exoplanets that are possibly hospitable to life, as changes in albedo could indicate changing cloud cover, weather, and large amounts of liquid—possibly even seas—on their surfaces. Understanding darkness and light has a broad spectrum of implications.

Dark and Light

The word albedo derives from an ancient language (in Latin, *albus* means *white*), but the term's use in science has a relatively modern origin: It first appeared in a 1760 treatise on optics by Swiss polymath Johann Heinrich Lambert. Since then, the term has become especially useful in astronomy, planetary science, and climatology.

Open ocean and ice exhibit a big disparity in albedo. Sea ice covered with fresh snow reflects roughly 85% of the sunlight that falls on it, whereas open Arctic waters reflect only about 7%. Image credit: Shutterstock/Maxim Tupikov.

Long-term fluctuations in an exoplanet's albedo could enable astronomers to generate crude "maps" of its surface—such as this one created by researchers using observations of Earth—and might help identify exoplanets hospitable to life. Image credit: Reproduced from ref. 6 by permission of the American Astronomical Society (AAS).

In the strictest sense, albedo—or *whiteness*—is defined as the proportion of light reflected from a surface.

Seen from space, Earth is a patchwork of darkness and light, from bright white ice caps and clouds to super-dark lava beds and everything in between. On average, though, about 30% of the sunlight that falls on Earth bounces back to space. "That has a big effect on the climate of the planet," says Drew Shindell, a climate scientist at Duke University in Durham, NC. In particular, planetary albedo helps determine Earth's average temperature. If albedo rises (meaning that more light gets reflected back to space), all other things staying equal, our planet gets a tad cooler.

Earth's albedo is fairly stable over the long run but can vary in the short term—say, for example, after a major volcanic eruption. Such events can spew large amounts of sulfur dioxide, which combines with water vapor to create light-scattering droplets of sulfuric acid. If a substantial number of those aerosols get pumped into the stratosphere, where they can persist much longer than they do at lower altitudes, Earth can be cooled substantially for months. Case in point: In the wake of the 1991 eruption of the Philippines' Mount Pinatubo, Earth's average temperature dropped below average for more than a year and, at peak cooling, fell about 0.7 °C. That sort of cooling effect is actually the idea behind one controversial means of geoengineering the climate—using high-flying aircraft, similar to those used for inflight refueling of military planes, to spray sulfuric acid droplets into the stratosphere.

While tweaking Earth's albedo on high can have global ramifications, changes in albedo at Earth's surface can have significant regional effects. Dust or soot on a snowpack can cause it to melt faster than normal (1), shifting the times when runoff occurs—which, in turn, could affect farmers and cities downstream that rely on that water. Deforestation or other changes in land use can lighten or darken Earth's surface. But one of the most striking such changes is unfolding in the

Arctic, says Mark Serreze, an Arctic climate scientist at the University of Colorado Boulder.

Icy Feedback

There's a big contrast in albedo between ocean and ice. Sea ice that's covered with fresh snow reflects about 85% of the sunlight that falls on it, says Serreze. But open water in the Arctic Ocean reflects only 7% or so. That dramatic difference sets up a feedback that has, over a period of decades, resulted in summer sea ice in the Arctic becoming younger, thinner, and less extensive.

Research findings from recent years suggest the process unfolds in multiple steps (2). Under the round-the-clock sun of an Arctic summer, any part of the ocean not covered by sea ice absorbs sunlight and warms up. That tends to melt the edges of the floating ice nearby, expanding the open areas—which then allows even more of the sea to warm up, says Serreze. Those warm, open areas don't build up as much ice over the subsequent winter, which means that melting the following spring has that much more of a head start. Recent computer simulations by other researchers have revealed that the more sparse the Arctic sea ice is, the more it can be spread around by winds and currents (3)—a process that accelerates summer melting even further.

The scope and magnitude of feedbacks such as these, both on a regional and a global scale, are some of the largest uncertainties in current climate models, according to the Intergovernmental Panel on Climate Change (4). For instance: As the planet warms, what effect will rising global temperatures have on the amount and brightness of Earth's cloud cover? How might droughts or deforestation change Earth's albedo in some regions? And because climate is such a complicated system, how will these feedbacks influence each other? "We should never be looking at feedbacks in isolation, because everything depends on everything else," says Serreze.

Eyes to the Sky

On a crisp, bright February morning in 2013, a 20-meter-diameter asteroid blazed into the atmosphere and exploded high over Chelyabinsk, Russia, with an energy around 30 times that of the atomic bomb detonated over Hiroshima, Japan. Because the object approached our planet from the direction of the sun, it hadn't been seen before it struck. Could an even larger object slam into Earth? The odds are low, but researchers have no precise notion of how low they are. Albedo has long helped astronomers estimate those odds.

Most asteroids—either because they are too small or too far away or both—show up in images as a single point of light, so it's not possible to directly measure their size. Lacking better data, astronomers have to estimate an object's size based on its overall brightness, its distance from Earth, and its presumed albedo. There's one small problem, though, says Vishnu Reddy, a planetary scientist at the University of Arizona in Tucson.

Asteroids have a wide range of reflectivities that depend on their composition. Carbon-rich asteroids can reflect as little as 2% of the light that falls on them, Reddy notes. Other types, including silicon-rich stony asteroids, have an albedo that's 10 or more times that. Thus, uncertainty in an asteroid's albedo results in a wide range of possible sizes, and that, in turn, makes it difficult to predict whether an object is small enough to break apart high in the atmosphere, big enough to reach lower altitudes or perhaps even large enough to punch through the atmosphere and hit the ground.

In the past decade or so, astronomers have expanded their analytical toolbox and used a space-based satellite to measure the radiation that an asteroid emits at infrared wavelengths. Those data typically yield a much tighter size range than estimates based solely on albedo do, Reddy notes. But albedo is still used to develop initial estimates of asteroid size. And reflectivity is useful for other sorts of astronomical analyses too.

Data gathered by ground-based instruments and reported in the 1950s revealed that the brightness of Pluto varied regularly. The Hubble Space Telescope—in whose camera Pluto spans less than three pixels—later confirmed those observations. Rather than having a consistently bright surface, the dwarf planet seemed to be patchy (5)—dark in some spots but bright in others, says Alan Stern, planetary scientist at Southwest Research Institute in Boulder, CO, and principal investigator of the New Horizons mission that swept past Pluto in July 2015. Close-up images of the icy orb gleaned during the flyby, when intentionally blurred to simulate views from a large distance, largely match maps generated long before the flyby occurred, he notes.

The same sort of observation techniques could be used to analyze exoplanets circling distant suns, researchers note. To demonstrate the procedure, Siteng Fan, a planetary scientist at the California Institute of Technology in Pasadena, and his colleagues pursued a different perspective, aiming to figure out how Earth might appear from a distant solar system (6). They analyzed data gathered by a space-based telescope positioned about 1 million kilometers sunward from Earth. From that position, the probe can continually take pictures of a fully sunlit Earth. The team examined sets of images taken nearly simultaneously at 10 different wavelengths, each set taken every one to two hours over the course of two years,

says Fan. For each image, they calculated Earth's overall reflectance and presumed—as would be true from a distant alien's point of view—that the light gathered by the sensors came from a single point of light. Then they strung those data sets together and studied how Earth's albedo varied over the two-year interval.

Using a statistical method known as principal component analysis, the team found two major sources of variation: one that was linked to features such as continents and the clouds associated with them, and another that could be attributed to clouds that weren't connected to landmasses. The findings, they argue in the August *The Astrophysical Journal Letters*, demonstrate that statistical approach could be used to distinguish exoplanets that have some sort of weather from those with an unchanging face due to a complete shroud of clouds or a total lack thereof (6).

"Right now, the effects of cloud changes on climate are very uncertain."

—Drew Shindell

Results also enabled the researchers to make a crude map of Earth's continents and to determine that our planet rotates once every 24 hours. "It's amazing to think that you can get all that information from a single dot of light," says Fan.

Although long-term measurements of reflectance may shed new light on distant planets, further studies of albedo—both on a regional and a global scale—could lead to major improvements in climate models here on Earth. For one thing, better notions of the sunlight-scattering capabilities of dust, clouds, and anthropogenic pollutants such as aerosols from smokestacks and vehicle tailpipes could decrease the uncertainty now inherent in complex simulations of climate. For example, pollutants can change the size of water droplets in a cloud, thus changing its reflectivity and making it brighter. And by making individual droplets smaller, these pollutants can also render such clouds less likely to rain. How those particular changes, in turn, affect other factors that also affect global temperatures and precipitation are, well, up in the air. "Right now," says Shindell, "the effects of cloud changes on climate are very uncertain."

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