PALEOCLIMATOLOGY

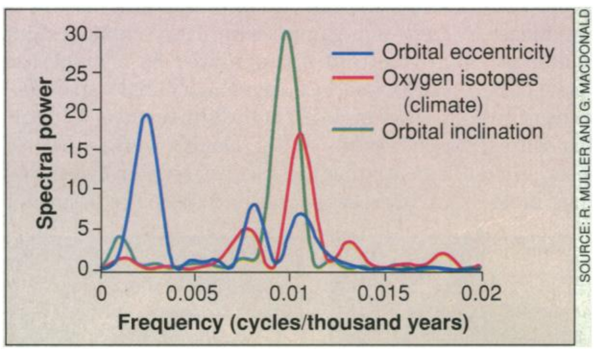
Upstart Ice Age Theory Gets Attentive But Chilly Hearing

Selling a new gizmo to replace a longtime favorite is always a tough job—especially if few are convinced that the original is broken. Physicist Richard Muller of the University of California, Berkeley, knows what it's like: For several years, he has been pitching a new way to drive the comings and goings of the ice ages. He's trying to displace the cherished Milankovitch mechanism in which cyclical changes in the elliptical shape of Earth's orbit shift the pattern of solar heating, triggering the buildup or melting of ice sheets.

Now, on page 215 of this issue of *Science*, Muller and geophysicist Gordon MacDonald of the International Institute for Applied Systems Analysis in Laxenburg, Austria, present what they consider their strongest statistical evidence yet that the ice ages are instead driven by a different orbital mechanism—changes in the inclination of Earth's orbit relative to the plane of the solar system. These orbital shifts would periodically dip Earth into a climate-altering cosmic dust cloud, Muller theorizes. Applying a statistical technique called spectral analysis to new climate records, he and MacDonald now offer evidence that changing orbital inclination provides a better fit to the cyclical timing of the ice ages than traditional Milankovitch mechanisms.

So far, their radical idea is winning only scattered, cautious support. Oceanographer John Imbrie of Brown University, who in the 1970s helped convert his colleagues to the Milankovitch mechanism, says, "The statistical evidence [for inclination] is very good. [It] might play a role." But most of the paleoclimate community isn't ready to dethrone their well-established favorite without a fight. Some take issue with the statistical methods, while others point out that there's no known—or as yet imagined—way for interplanetary dust clouds to plunge Earth into an ice age. At a small workshop held last year to give Muller a platform, the general conclusion was that "his arguments would just not sell," says geophysicist and climate modeler Richard Peltier of the University of Toronto. Even Muller sees a long road ahead: "I know it's an uphill battle," he says.

To fight that battle, Muller and MacDonald are enlisting the same climate records that paleoclimatologists have been dissecting for the past 15 years. These consist of oxygen-isotope compositions of microfossils deposited on the sea floor during the past 600,000 years. The changing ratio of oxygen-18 and oxygen-16 isotopes reflects the changing volume of glacial ice around the world. Muller and MacDonald applied a statistical technique called spectral analysis to the oxygen-isotope records from eight sediment cores at sites around the world's oceans; the method can pick out distinct cycles from a record jumbled by other cycles and noise. They found that ice volume waxed and waned with a single period of about 100,000 years—exactly the period over which the plane of Earth's orbit gently nods a few degrees above and below the plane of the solar system.



Battling curves. The single cycle of Earth's changing orbital inclination (green) seems a better match to climate (red) than the multiple cycles of orbital eccentricity (blue).

A single climate cycle of 100,000 years doesn't quite match what the Serbian astronomer Milutin Milankovitch predicted in 1941. Milankovitch and later workers calculated that gravitational perturbations of the planets would cause the shape of Earth's orbit, or its eccentricity, to vary with three different periodicities: 400,000, 125,000, and 95,000 years. If these eccentricity variations translated directly into climate variations, spectral analysis of the climate records should reveal three cycles centered on those three frequencies. However, the 400,000-year peak—predicted to be the strongest—has never shown up in records of ice volume. Since the 1970s, other workers who saw signs of a 100,000-year cycle assumed that it was the signature of the other two eccentricity cycles blurred into one. But Muller says it's simply a clear signal of orbital inclination. "Inclination is a good match to the data and eccentricity really isn't," says Muller. "That's just a devastating problem."

But not everyone is wowed by Muller and MacDonald's application of spectral analysis. "I was never impressed with that whole argument," says mathematician David Thomson of Lucent Technologies' Bell Labs Innovations in Murray Hill, New Jersey, a specialist in time-series analysis. With a short climate record—and there are only six or seven 100,000-year cycles in the record—the power of spectral analysis is greatly diminished, he says. Pinning down precise frequencies or even distinguishing two cycles of similar frequency is problematic. Imbrie agrees. "Different people can come up with different spectra" from the same data, he says. "I don't think that's the best way to look at it."

Imbrie and others favor an ice-age-by-ice-age comparison of the isotopic record and orbital perturbations instead. Muller and MacDonald did just that last year in a paper in *Nature* and found that times of maximum inclination consistently preceded glacial maxima, albeit by a hefty 33,000 years. But a similar study by paleoceanographer Maureen Raymo of the Massachusetts Institute of Technology favors eccentricity.

In work forthcoming in *Paleoceanography*, Raymo calculated the effect of eccentricity combined with that of two other Milankovitch orbital variations, the tilting of Earth's axis of rotation (which has a period of 41,000 years) and the wobbling of the axis (which has a period of 23,000 years). She compared 11 lengthy isotopic records with the predicted effects of these combined orbital variations on climate. Milankovitch had reasoned that summer temperatures in high northern latitudes, where the great ice sheets formed, should affect whether each year's snows melted away or accumulated into a glacier. Raymo found that the ice ages consistently ended after the combined Milankovitch variations created a period of warm summers in these latitudes. That convinces her that the Milankovitch cycles were indeed triggering the ice ages—and that "orbital inclination has nothing to do with it."

Imbrie notes, however, that "the two theories are not mutually exclusive." He too has done a termination-by-termination comparison and finds that both eccentricity and inclination have kept the same pace as the waxing and waning of the ice. "There is a surprisingly strong statistical match for inclination," says Imbrie. "The problem is far from solved."

While the statistical arguments run on, other paleoclimatologists see an even larger problem with Muller's idea: How could a changing inclination send Earth into a deep freeze? If inclination is to be proven, says paleoclimatologist André Berger of the

Catholic University of Louvain in Belgium, "we must find a physical process that will convince me that the inclination is the key factor in creating the 100,000-year cycle. The only answer for me is the physical mechanism."

The only possible agent of climatic change Muller can cite is the dust that asteroids and comets spew across the solar system. Asteroid dust remains largely in a disk across the solar system, and Earth periodically dips in and out of that disk as inclination varies. This interplanetary dust filters into Earth's upper atmosphere, but it has no known influence on climate. "I have to confess, I don't have a physical mechanism that works," Muller admits. "But part of the problem is our ignorance of the atmosphere and [the dust in] the nearby solar system."

Muller also points out that the physical mechanism behind the Milankovitch cycles—the amount of sunshine reaching high northern latitudes—is far from perfect. "The only real defense I have," he says, "is that if you look carefully at the Milankovitch model, the physical mechanism there was always hand waving, too." Indeed, paleoclimatologists have long recognized that the amount of Milankovitch-induced change in solar heating is too small to melt glaciers or to send Earth into a deep freeze, unless some as yet unidentified part of the climate system amplifies it.

Still, even a partial physical mechanism is better than none, researchers say. "Even though you can't pin down exactly why Earth's climate responds to Milankovitch [orbital] cycles, at least there is some physical connection, whereas Rich Muller has none," responds oceanographer Wallace Broecker of Columbia University's Lamont-Doherty Earth Observatory, who in 1970 first found a 100,000-year isotopic cycle and noted that it was roughly in step with eccentricity. "It would be hard to believe this tiny influx of dust could be having such a profound effect on climate."

"I think the chances that the 100,000-year cycles are due to inclination are exceedingly small," says Broecker, but the challenge to Milankovitch "has been healthy, because [Muller] made everybody stand up and defend what they thought. It's a fascinating problem—but unresolved."

–**Richard A. Kerr**

EVOLUTIONARY BIOLOGY

Sizing Up Dung Beetle Evolution

BOULDER, COLORADO—Imagine 120-kilogram antlers on an 800-kilogram moose, and you will have an idea of the outlandish proportions of the horns on some male dung beetles. The horns, which males of the genus *Onthophagus* use to repel competing suitors, have awed evolutionary biologists since Charles Darwin. Among other things, biologists have wondered what keeps the horns from getting even bigger. New experiments on these beetles now confirm a long-standing suspicion about such exaggerated traits. Horn size is limited, the studies show, because horns exact a high cost during the beetles' development: the bigger the horns, the smaller other nearby body parts.

Biologists from Darwin on have speculated about these kinds of trade-offs between body parts, but researchers had found few concrete examples. At the annual evolution meetings here,* however, evolutionary biologist Douglas Emlen of the University of Montana, Missoula, reported selective breeding and hormone experiments showing that boosting the development of *Onthophagus* males' horns causes the beetles to form smaller eyes; artificially restricting horn size leads to bigger eyes. This link, Emlen said in his talk, suggests that horns are indeed costly—and that beetles who squander too much on them are likely to be blind sided by natural selection.

The work also supports the notion that some changes in development may be a "zero-sum game," with every enhancement in one trait compensated by a reduction somewhere else, says Hugh Dingle, an evolutionary biologist at the University of California, Davis. "What Doug's work shows so nicely is that these [constraints on evolution] involve—as people have been predicting for a long time but haven't been able to show—clear trade-offs between structures."


D. EMLEN

Horns aplenty. Male dung beetles with short horns *(left)* have relatively big eyes, but big-horned beetles have tiny eyes.

Emlen, who won the American Society of Naturalists' Young Investigator Prize for his study, began his beetle work as a graduate student at Princeton University. He found that *Onthophagus* beetles have a developmental switch that turns on horn growth only if the larva has acquired enough reserves, such as body fat, before it metamorphoses into an adult beetle. Without enough fat, the larva has to save its resources to produce other adult structures and can't afford to make horns at all.

To test Darwin's suspicion that neighboring structures compete for finite resources during development, Emlen restudied the beetle specimens of his graduate work while doing a postdoctoral stint in the lab of Duke University entomologist Frederik Nijhout. He found that in *Onthophagus*, which has horns that develop just above the eyes, males with big horns did tend to have proportionally smaller eyes. "But this was just a correlation," as Emlen says; demonstrating an actual developmental trade-off would require manipulating the system.

So he and Nijhout applied juvenile hormone, which delays metamorphosis in beetles, to the beetle larvae. This postponed the onset of horn growth, producing adult males with shorter horns than untreated males. The only other trait that differed systematically between treated and control beetles was eye size: Short-horned beetles had bigger eyes.

Emlen had no comparable method to artificially make horns bigger, but he bred the beetles for seven generations and selected for large horns. The big-horned products of such selections had tiny eyes, he found, with fewer units in their compound eyes and, thus, a restricted field of vision. Carried to an extreme, Emlen says, big horns could even lead to blindness. That demonstration, says University of Maryland, College Park, evolutionary biologist Gerald Wilkinson, is "a neat trick. ... People have been writing papers about these organisms for 100 or more years, but they have all been comparative" rather than experimental.

Of course, this is just one case, and researchers exploring the links between evolution and development want more examples (*Science*, 4 July, p. 34–39). But Emlen and Nijhout say that dung beetles can likely help out. For almost every body part, there's a horn sprouting close by in one dung beetle species or another, says Emlen: "The huge variation in the morphology and location of horns should give us a big opportunity to predict how development constrains evolution."

–**Wade Roush**

* Joint meetings of the Society for the Study of Evolution, the American Society of Naturalists, and the Society of Systematic Biologists, Boulder, Colorado, 14–18 June.