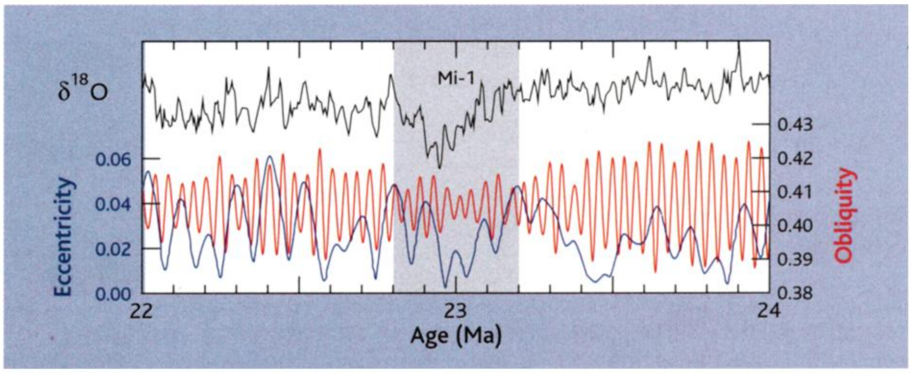
"It's the first really intriguing connection between M-theory and cosmology," says Spergel. "This is sort of an Ur–big bang." And although ekpyrotic theory might seem like an import from cloud-cuckoo-land, future real-world experiments should be able to tell whether it or inflation is correct. The two models send different sorts of gravitational waves rattling around the universe—waves that might one day be detectable by successors to current gravitational-wave experiments.

Experimental verification might take a less welcome form. The model's name, Steinhardt explains, comes from the Stoic term for a universe periodically consumed in fire. That is because at any moment another membrane could peel off, float toward us, and destroy our universe. Indeed, Steinhardt says, we might have already seen the signs of impending doom. "Maybe the acceleration of the expansion of the universe is a precursor of such a collision," he says. "It is not a pleasant thought."

–CHARLES SEIFE

PALEOCLIMATOLOGY

An Orbital Confluence Leaves Its Mark



Two wiggles make an ice age. The cyclic nodding of Earth on its rotation axis (red) nearly steadied 23 million years ago and the periodic elongation of its orbit (eccentricity, blue) nearly disappeared, leading to an ice age (dip in black curve).

CREDIT: J. ZACHOS ET AL.

Whenever they could, the 19th century geologists who split time into epochs chose as a boundary a grand transformation of the period's dominant animal group. But some intervals dragged on for so long without an appropriate transformation that geologists chose another marker to break them up. For the division between the Oligocene and the Miocene, they picked an episode of sediment erosion. At the time, nobody knew its ultimate cause. Now, paleoceanographers have finally put their finger on it—and in the process, they've identified a new way to make an ice age.

On page 274 of this issue, paleoceanographer James Zachos of the University of California, Santa Cruz, and colleagues report that 23 million years ago a rare combination of the shape of Earth's orbit and the tilt of its rotation axis led to a brief climatic cooling and buildup of ice on Antarctica. This, in turn, lowered sea level and exposed the shallow sea floor to erosion, creating the Oligocene-Miocene boundary. The convergence of orbital variations would be "a very reasonable explanation" for the glacial boundary event, says paleoclimate modeler Thomas Crowley of Texas A&M University in College Station, as well as further support for the power of orbital variations to influence climate.

New insights into climatic events of the Oligocene-Miocene transition come from sediment laid down between 20 million and 25.5 million years ago in the western equatorial Atlantic and retrieved in two Ocean Drilling Program cores. From these two cores, Zachos and colleagues extracted complete, finely detailed records of two sets of stable isotopes preserved in the carbonate skeletons of microscopic bottom-dwelling animals called foraminifera. The changing ratio of oxygen-18 to oxygen-16 along a core reflects varying bottom-water temperature as well as changes in the volume of glacial ice in the world. The ratio of carbon-13 to carbon-12 reflects changes in the geochemical cycling of carbon, in this instance most likely due to changes in the productivity of ocean plants. Zachos and colleagues developed a time scale by matching cyclic variations in core sediment properties, such as color, to changes in the shape or eccentricity of Earth's orbit and in Earth's axial tilt, each of which keeps a steady orbital beat through the ages. Then they applied this scale to their isotope records.

The time scale allowed them to determine the pace of climate and carbon-cycle changes. Now they could compare the timing of events on Earth with that of orbital cycles. They found that ocean climate throughout the 5-million-year record varied in step with orbital variations, from the 400,000-year and 100,000-year variations in orbital eccentricity to Earth's 41,000-year nodding as it changes tilt. And the strength of the climate response varied in proportion to the strength of the orbital variation, especially in the case of the 100,000-year variation. Such strict correlation, with climate lagging slightly behind orbital variations, convinced them that the orbital variations were altering climate back then. When eccentricity was low, climate cooled. It also cooled when tilt steadied to only modest variations without excursions to high tilt.

Those are the same climate-orbit relations invoked to explain climate change during the past million years, including the coming and going of the ice ages tied to changing eccentricity. In the case of tilt, the connection between orbital variation and climate is straightforward—when the planet tilts far over, high-latitude land gets extra sunlight and warmth in the summer, discouraging the year-to-year accumulation of snow that would otherwise form ice sheets. When tilt is low, there's less summer sunlight in the high latitudes and glaciation picks up.

Inspecting the entire 5-million-year record, Zachos and colleagues found one geologic moment when the orbital forces for climatic cooling and ice sheet building came together. At 23.0 million years ago, eccentricity dropped to low levels and variations in tilt nearly disappeared. Simultaneously with these ideal orbital conditions for ice sheet formation, bottom waters cooled and ice volume increased. An ice age had arrived, at least by the standards of a time when ice was typically limited to modest amounts on Antarctica. When the orbital confluence disappeared, 200,000 years later, so did the extra ice. The excursion into deeper glaciation may have been helped along, they say, by a preceding million-year-long decline in the greenhouse gas carbon dioxide that is suggested by the trend in carbon isotope composition.

Researchers are pleased that there's more to the Oligocene-Miocene boundary than a conveniently timed gap in sedimentation. "It's a fabulous data set," says paleoceanographer Kenneth Miller of Rutgers University in Piscataway, New Jersey. The coincidence of an "orbital anomaly"—simultaneous extremes of two different orbital variations—and a major climate event suggests a new way for orbital variations to trigger climate change, says Crowley. "The idea that 'cold' summer orbits drive you into glaciation and 'hot' summer orbits drive you out is one of the linchpins" of the orbital theory of climate, he says. At the Oligocene-Miocene boundary, climate seems to shift under an orbital double whammy.

–RICHARD A. KERR