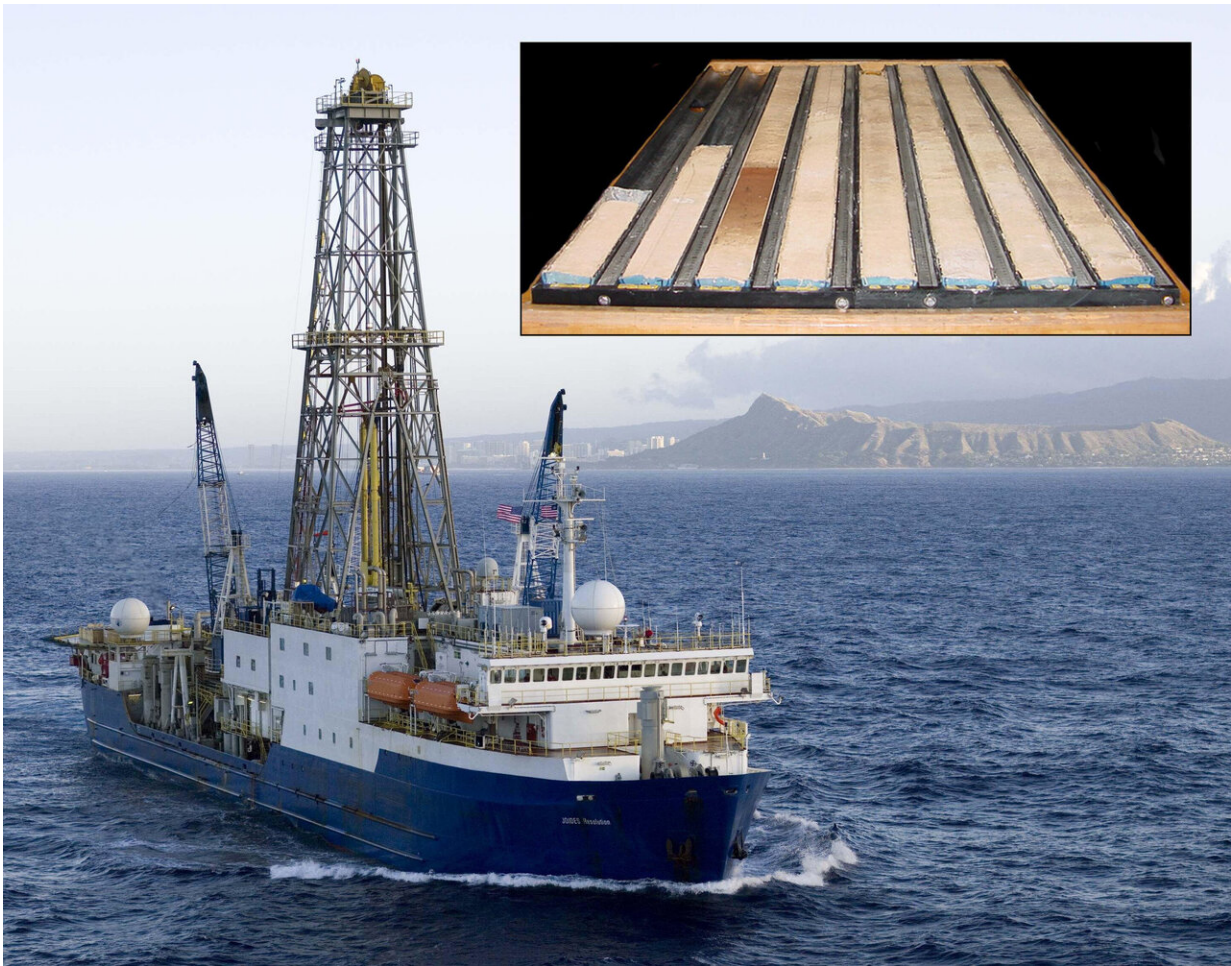


# Deep-sea sediments reveal solar system chaos: An advance in dating geologic archives

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Scientific drilling ship JOIDES Resolution. The sediment archives obtained during ocean drilling programs give scientists a glimpse into Earth's climatic history and reveal chaos in the Solar System. Inset: Deep-sea sediment cores across the Paleocene-Eocene boundary. The sections of light brown color consist mainly of calcium carbonate, whereas the dark red/brown section is a clay layer,

representing the onset of an interval of intense global warming and ocean acidification 56 million years ago, known as the Paleocene-Eocene Thermal Maximum. Credit: Integrated Ocean Drilling Program

A day is the time for Earth to make one complete rotation on its axis, a year is the time for Earth to make one revolution around the Sun—reminders that basic units of time and periods on Earth are intimately linked to our planet's motion in space relative to the Sun. In fact, we mostly live our lives to the rhythm of these astronomical cycles.

The same goes for climate cycles. The cycles in daily and annual sunlight cause the familiar diel swings in temperature and the seasons. On geologic time scales (thousands to millions of years), variations in Earth's orbit are the pacemaker of the ice ages (so-called Milankovitch cycles). Changes in orbital parameters include eccentricity (the deviation from a perfect circular orbit), which can be identified in geological archives, just like a fingerprint.

The dating of geologic archives has been revolutionized by the development of a so-called astronomical time scale, a "calendar" of the past providing ages of geologic periods based on astronomy. For example, cycles in mineralogy or chemistry of geologic archives can be matched to cycles of an astronomical solution (calculated astronomical parameters in the past from computing the planetary orbits backward in time). The astronomical solution has a built-in clock and so provides an accurate chronology for the geologic record.

However, geologists and astronomers have struggled to extend the astronomical time scale further back than about fifty million years due to a major roadblock: solar system chaos, which makes the system unpredictable beyond a certain point.

In a new study published in the journal *Science*, Richard Zeebe from the University of Hawai'i at Manoa and Lucas Lourens from Utrecht University now offer a way to overcome the roadblock. The team used geologic records from deep-sea drill cores to constrain the astronomical solution and, in turn, used the astronomical solution to extend the astronomical time scale by about 8 million years. Further application of their new method promises to reach further back in time still, one step and geologic record at a time.

On the one hand, Zeebe and Lourens analyzed sediment data from drill cores in the South Atlantic Ocean across the late Paleocene and early Eocene, ca. 58-53 million years ago (Ma). The sediment cycles displayed a remarkable expression of one particular Milankovitch parameter, Earth's orbital eccentricity. On the other hand, Zeebe and Lourens computed a new astronomical solution (dubbed ZB18a), which showed exceptional agreement with the data from the South Atlantic drill core.

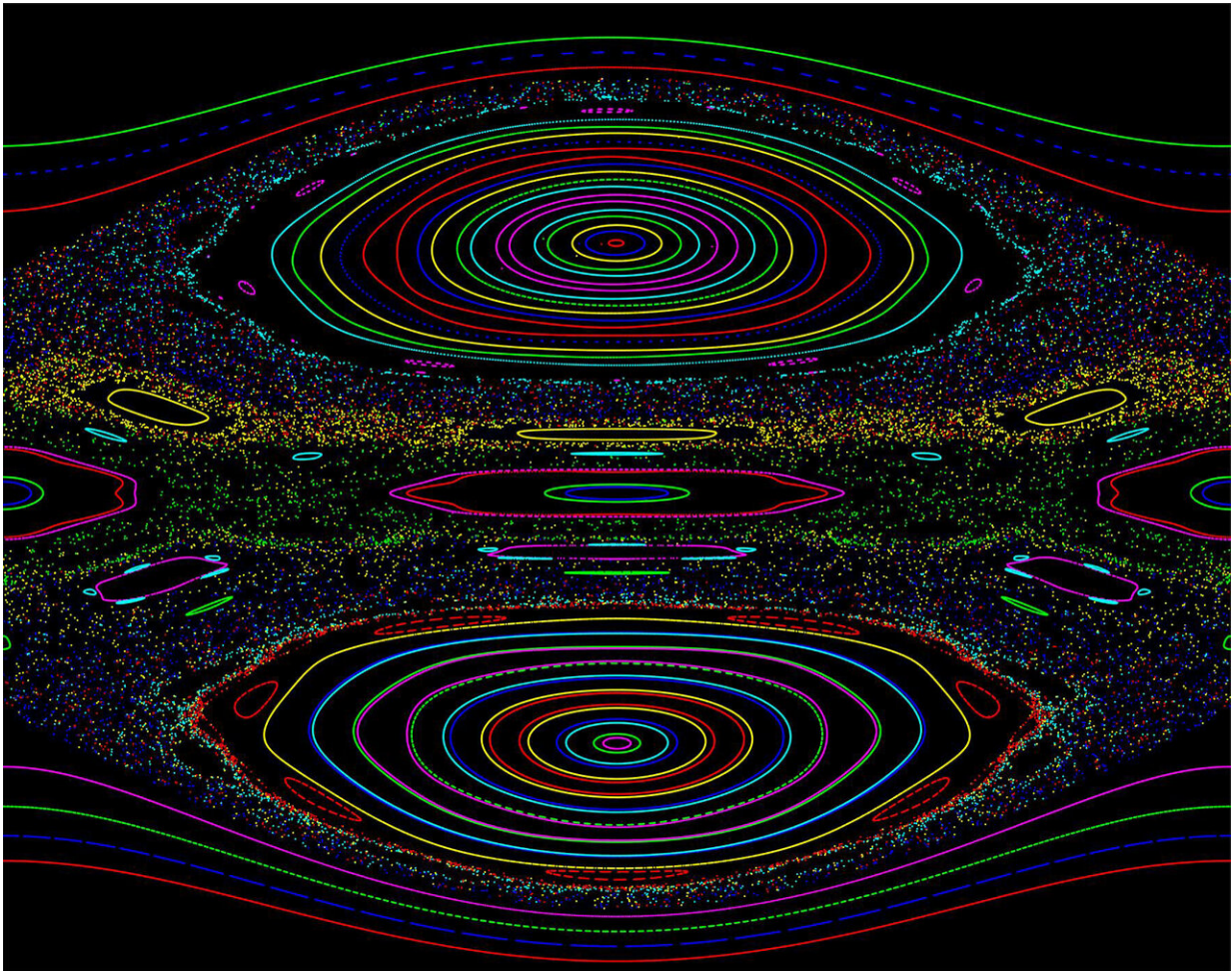


Illustration of chaotic trajectories (Poincaré section, velocity vs. position) in a simple dynamic system (forced pendulum) from overlapping resonances. Structures of closed curves that appear like rings on a shooting target are regions of stability, whereas densely filled, dotted areas are regions of chaos. Interacting resonances are also suspected to cause chaos in the Solar System, although significantly more complex than the simple system depicted here. Credit: Richard Zeebe

"This was truly stunning," Zeebe said. "We had this one curve based on data from over 50-million-year-old sediment drilled from the ocean floor and then the other curve entirely based on physics and numerical

integration of the solar system. So the two curves were derived entirely independently, yet they looked almost like identical twins."

Zeebe and Lourens are not the first to discover such agreement—the breakthrough is that their time window is older than 50 Ma, where astronomical solutions disagree. They tested 18 different published solutions but ZB18a gives the best match with the data.

The implications of their work reach much further. Using their new chronology, they provide a new age for the Paleocene-Eocene boundary (56.01 Ma) with a small margin of error (0.1%). They also show that the onset of a large ancient climate event, the Paleocene-Eocene Thermal Maximum (PETM), occurred near an eccentricity maximum, which suggests an orbital trigger for the event. The PETM is considered the best paleo-analog for the present and future anthropogenic carbon release, yet the PETM's trigger has been widely debated. The orbital configurations then and now are very different though, suggesting that impacts from orbital parameters in the future will likely be smaller than 56 million years ago.

Zeebe cautioned, however, "None of this will directly mitigate future warming, so there is no reason to downplay anthropogenic carbon emissions and [climate change](#)."

Regarding implications for astronomy, the new study shows unmistakable fingerprints of solar system chaos around 50 Ma. The team found a change in frequencies related to Earth's and Mars' orbits, affecting their amplitude modulation (often called a "beat" in music).

"You can hear amplitude modulation when tuning a guitar. When two notes are nearly the same, you essentially hear one frequency, but the amplitude varies slowly—that's a beat," Zeebe explained. In non-chaotic systems, the frequencies and beats are constant over time, but they can

change and switch in chaotic systems (called resonance transition). Zeebe added, "The change in beats is a clear expression of chaos, which makes the system fascinating but also more complex. Ironically, the change in beats is also precisely what helps us to identify the solution and extend the astronomical time scale".

**More information:** R.E. Zeebe at University of Hawaii at Manoa in Honolulu, HI et al., "Solar System chaos and the Paleocene–Eocene boundary age constrained by geology and astronomy," *Science* (2019). [science.sciencemag.org/cgi/doi ... 1126/science.aax0612](https://science.sciencemag.org/cgi/doi/10.1126/science.aax0612)

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