weakening the proposal of a bacterial origin for these protosteroids is the occurrence of 4,24-dimethyl triaromatic steroid around 1,300 million years ago, the potential precursors of which have not been observed in bacterial extracts.

Yet, as Brocks and colleagues indicate, contributions from bacteria, living or extinct, to the steroid landscape cannot be fully ruled out. Before the time of the LECA, the ability to form protosterols was most probably also present in extinct eukaryotic relatives – such species are known as stem-group eukaryotes. This capacity to form protosterols might have been transferred from ancient bacteria to eukaryotes through a process called horizontal gene transfer[7], although some argue that this transfer occurred in the reverse direction[5,6].

For 640 million years of the mid-Proterozoic era, protosterols were the main, if not the only, steroid players. In the Tonian period, after an approximately 200-million-year-long data gap, at around 800 million years ago, the protosterol world seems to have declined, whereas crown steroids progressively took over the landscape of aromatic steroids. The Tonian is already considered a key interval of Earth's history on the basis of a molecular fossil distribution that reflects the transition from a bacterium-dominated marine ecosystem to a crown-eukaryote-rich environment that also included red algae[8]. Now, the Tonian period might be known as the time when crown eukaryotes took over marine ecosystems at the expense of protosteroid-producing stem-group eukaryotes.

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The author declares no competing interests.

Metrology

Clocks synchronized at the quantum limit

David Gozzard

Time signals have been transmitted across 300 kilometres with an accuracy and precision limited only by the quantum nature of photons. The feat promises to revolutionize high-precision science using satellites. **See p.721**

Communications networks, satellite navigation and fundamental-physics experiments that test the general theory of relativity are just a few of the diverse systems that rely on networks of modern atomic clocks. These clocks are precise to a few parts in 10^{18}, which is roughly equivalent to being able to measure the time between now and the Big Bang with an uncertainty of only one second[1]. However, to take advantage of this precision, the time signal from the atomic clock needs to be transmitted reliably. On page 721, Caldwell *et al.*[2] demonstrate a technique that could be used to transmit atomic-clock time signals between Earth and satellites without compromising the signals' precision and accuracy, which are limited only by the quantum nature of light.

Atomic clocks keep time using the frequency of light emitted by electrons as they transition between energy states in an atom. Optical atomic clocks use intersecting laser beams to trap the atoms, and these beams are engineered so that the frequency of the laser light has very little effect on that emitted by the electrons. Time signals from optical atomic clocks need to be transmitted using lasers that send these signals through fibre-optic cables or through the air, in a process called optical

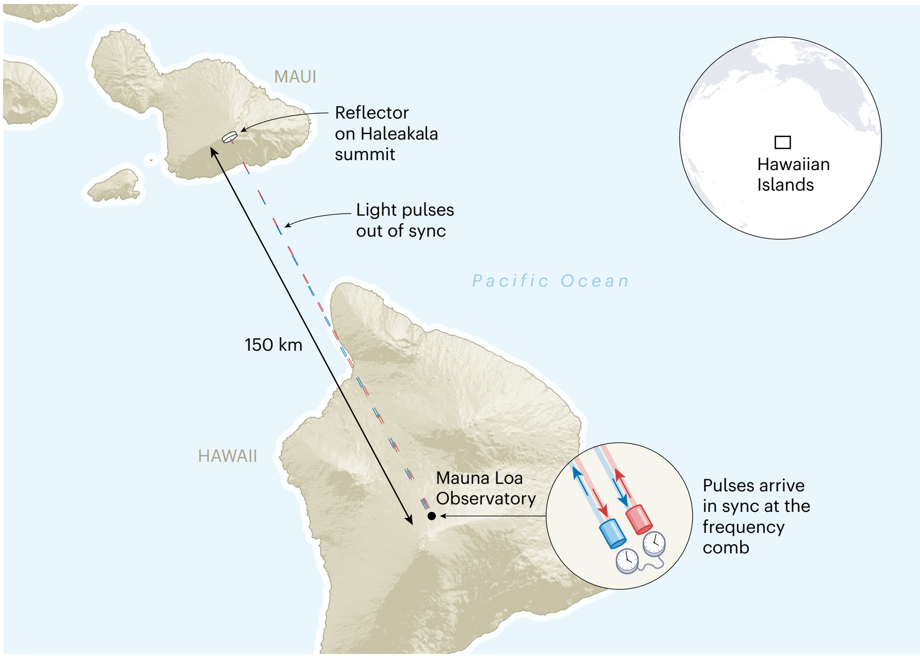

Figure 1 | Precise time synchronization between distant clocks at the quantum limit. Optical atomic clocks are high-precision timekeepers, but using them in networks (for example, those linking Earth with satellites) requires time signals to be transferred with similar precision. Caldwell *et al.*[2] paired such clocks with optical frequency combs (lasers producing precise, regular light pulses) to transmit a reflected signal between the Hawaiian volcanoes Mauna Loa and Haleakala and back – a distance of 300 kilometres. They used the arrival-time difference of pulses sent from one clock–comb pair to the other to calculate the time difference between clocks with a precision that approached the quantum limit, which is set by the number of photons transmitted. The clocks were connected so that the time transfer could be verified, and the pulse rates of the two combs were adjusted to scan possible time differences before being steered to pulse in sync.

time transfer. To avoid reducing the accuracy of the timing in transfer, these transmission systems need to be more stable than the clocks themselves, but their stability is degraded by vibration and temperature changes near the fibre, or by turbulence in the air.

Members of the same team as that of Caldwell and colleagues previously demonstrated optical time transfer by pairing atomic clocks with optical frequency combs, which are lasers that produce extremely short, precise pulses of light[1]. One of the reasons these combs are so useful for precision measurements is that the pulses are generated at a very regular rate. By measuring the difference in the arrival time of pulses sent from two clock–comb pairs at either end of an optical link, the time difference between the clocks can be calculated, revealing how close they are to being synchronized. And because both combs send pulses simultaneously through the link, any degradation in timing precision caused by vibration or by air turbulence is eliminated.

Last year, such combs were used to transmit stable clock signals over a 113-kilometre link between two mountains[3]. However, the demonstration relied on high-power optical frequency combs to transmit and receive the signals, using telescopes that were fitted with complex optics systems to correct for the distortion of the comb signal caused by turbulence on the link. By contrast, Caldwell *et al.* transmitted such signals across 300 km using combs that require 200 times less power, and so were able to use smaller telescopes that didn't need corrective optics.

The authors showed that this system worked by sending signals between the Hawaiian volcanoes Mauna Loa and Haleakala, which are around 150 km apart (Fig. 1). The clocks were both stationed on Mauna Loa so that the accuracy and precision of the time transfer could be easily verified, and the signals were reflected from Haleakala to maximize the distance traversed. The authors optimized the optical time transfer so that it reached the quantum limit, at which the highest stability and precision possible is fundamentally limited by the number of photons being received from the combs.

To achieve this, Caldwell *et al.* used a device they had developed previously, known as a time-programmable frequency comb[4]. In research carried out before this innovation[1,3], the combs at either end of the link were set to pulse at different rates. Every so often, the pulses from each comb would align, allowing the time difference between the clocks to be measured. This enabled the time-transfer system to scan over a range of possible time differences between the two clocks, but because the rates were fixed, it also meant that most pulses from the combs were out of sync, so the majority of photons went unused.

The authors' time-programmable comb allowed them to precisely adjust the pulse rate so that the two combs could be brought in sync after an initial scan of the possible time differences. But despite this advance, photons were still lost as they traversed the 300 km of air between the transmitter and receiver — only around one in every 100 pulses from the combs resulted in a photon being detected at the other end of the link. However, by digital filtering and careful optimization of the comb's control system, the authors were able to use the few photons that were detected to enable efficient time transfer in spite of these losses.

One of the most promising aspects of Caldwell and colleagues' work is that it shows that the system could be used to span the distance between the ground and geostationary satellites, which orbit Earth at an altitude that allows them to stay over the same spot on Earth as the planet turns. And the combs required to transmit time signals successfully across this distance need only 4 milliwatts of power (a typical laser pointer emits 1 mW). The findings therefore open up the exciting prospect of performing fundamental-physics experiments with much higher precision than is possible with existing systems (see, for example, ref. 5). In particular, the efficiency of the authors' system makes it ideal for use on satellites, because its low power and small telescope apertures minimize its size and weight, and therefore the cost of the satellite.

However, major challenges remain in designing an optical time-transfer system capable of linking to satellites that are in close orbit around Earth. These satellites move at several kilometres per second relative to the ground station, resulting in frequency changes, known as Doppler shifts, that are large and rapidly varying. It will be extremely difficult to compensate for these effects at the precision needed for effective time transfer. And although optical links to geostationary satellites will open up a range of scientific experiments, many applications will require satellites in closer orbits.

More broadly, Caldwell and colleagues' feat represents the highest time-transfer precision that can be achieved at the 'standard' quantum limit. However, a technique called quantum squeezing, which reduces quantum uncertainty in one measurement by increasing uncertainty in another[6], could be used to push the limits of achievable precision further to keep up with developments in atomic-clock technology. For now, the team's work provides the most convincing demonstration so far that time signals from optical clocks could feasibly be transmitted between the ground and satellites — a prospect that will have far-reaching impacts on the use of satellites for fundamental and applied science.

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The author declares no competing interests.

Tumour biology

Ultraviolet light affects cancer evolution

Elli Papaemmanuil

Much remains to be discovered about how premalignant cells become cancer cells. An analysis of the development of a type of human leukaemia implicates ultraviolet light in triggering a rare form of cancer. **See p.834**

The factors that cause cancer to develop from premalignant cells at a single anatomical site are becoming clearer. However, the role of tissue-specific environmental pressures that drive these cellular lineages (clones) to cause the disease to spread is less well understood. On page 834, Griffin *et al.*[1] investigate the development of an aggressive form of leukaemia called blastic plasmacytoid dendritic cell neoplasm (BPDCN), which is often diagnosed by the presence of malignant cells in the skin. The authors' data show that the migration of a type of immune cell through the skin leads to the accumulation of DNA damage associated with exposure to ultraviolet (UV) light. This damage precedes