an image, but also in distinguishing different frequencies, which requires a richer infrared colour palette than the seven broad channels that Spitzer was able to offer.

JWST has solved this problem by offering high-resolution, multi-channel imaging, the power of which is on full display in Ray and colleagues' work. The authors used two channels with narrow and medium bandwidths that partially overlap, and attempted to isolate the source of light that Spitzer had previously observed at 4.5 µm. The nebulous appearance of the Spitzer signals in this range earned them the name of the green fuzzies. On the basis of their frequency, the signals were assumed to be closely identified with outflows from young stars[3], which were expected to contain either molecular hydrogen (H_2), carbon monoxide (CO) or both gases – showing up at roughly these wavelengths.

Ray *et al*. found emission associated with both carbon monoxide and molecular hydrogen in the 4.5–5 µm wavelength range – a close match to the green fuzzies captured by Spitzer. The researchers then compared the spatial distribution of the calibrated JWST data with that of the Spitzer data and found a striking similarity between the two. This provides a compelling argument that the green fuzzies do indeed correspond to CO and H_2 emission, and one that required only the information provided by JWST's infrared images, rather than any complicated modelling.

Astronomers often attribute the green emission to molecular hydrogen[4], scattered light or both[5], and this assumption has even been used to calibrate models (see, for example, ref. 3). But Ray *et al*. 'subtracted' H_2 from their CO data, and in doing so, produced an image that is particularly intriguing, because it offers a glimpse into the differences between jet and outflow emission. CO and H_2 are produced under different conditions, and separating the two is a crucial diagnostic in the modelling of interstellar shocks.

The JWST image (Fig. 1) suggests that CO emanates mostly from the inner regions of Herbig-Haro 211 and the very edges of the shock fronts, whereas the H_2 comes from the central column and the full breadth of nearly all the arcs that form the backbone of the outflow. It is therefore clear that H_2 can survive some shocks that destroy CO molecules. But the fact that CO can still be seen on the edges of the shocks implies that both gases contribute to the green fuzzies, challenging the assumption that the Spitzer signals are dominated by H_2 emission[3]. Alternatively, it could turn out that there is something special about the particular region around Herbig-Haro 211, or about the local area around outflows in general. Indeed, shocks that can destroy molecules have been seen in other protostellar outflow systems[6–8].

Other sources must be checked in a similar fashion to establish a rule of thumb. Ray and colleagues' results are certainly striking, but they are not without controversy. Careful modelling and analysis will be required before their conclusions can be applied more broadly to other young stars in our Galaxy. Once the true ratio of the two molecules is known, it can be used to calibrate the entire Spitzer data set, which is currently much larger than that of the young JWST.

Fundamentally, the great value of this comparison between JWST and Spitzer data results from the legacy of the earlier telescope; if such an interpretation can be applied broadly, then it enhances the analysis of all green fuzzies in the Spitzer archives. The value of legacy data cannot be understated. Spitzer's archival data set is not the only archival data set that can be used for comparison with a next-generation observatory. Many of the early discoveries from JWST have or will come about through comparison with other infrared space telescopes, such as NASA's Hubble Space Telescope, as well as ground-based facilities.

Indeed, when Ray and colleagues compared one of their images with one taken in 2002 by the European Southern Observatory's Very Large Telescope[9], the researchers found that the shock fronts had shifted significantly outward, travelling at speeds of around 100 km per second. Their interpretation is that the shocked regions are not actually moving this fast, but that successive portions of the cloud are lighting up as the jet passes underneath, like a string of festive light bulbs illuminating in rapid sequence. If the shocked regions themselves were moving at such incredible speeds, their molecules would be ripped apart, but this not consistent with the authors' observations.

Such revelations demonstrate the power of comparison over long timescales – as well as the fact that astrophotography need not be merely beautiful. Archival images will continue to have a key role in revealing the secrets of star formation while instruments become ever more advanced, as Ray and colleagues' intriguing study shows.

Joel Green is at the Space Telescope Science Institute, Baltimore, Maryland 21218, USA.
e-mail: jgreen@stsci.edu

1. Ray, T. P. *et al. Nature* **622**, 48–52 (2023).
2. Ortiz-León, G. N. *et al. Astrophys. J.* **865**, 73 (2018).
3. Yuan, Y., Neufeld, D. A., Sonnentrucker, P., Melnick, G. J. & Watson, D. M. *Astrophys. J.* **753**, 126 (2012).
4. Noriega-Crespo, A. *et al. Astrophys. J. Suppl. Ser.* **154**, 352–358 (2004).
5. Lee, H.-T. *et al. Astrophys. J. Suppl. Ser.* **208**, 23 (2013).
6. Dionatos, O., Ray, T. & Güdel, M. *Astron. Astrophys.* **616**, A84 (2018).
7. Harsono, D. *et al. Astrophys. J.* **951**, L32 (2023).
8. Lynch, C. J. R., Smith, M. D. & Glover, S. C. O. *Mon. Not. R. Astron. Soc.* **491**, 3082–3100 (2020).
9. Hirano, N. *et al. Astrophys. J.* **636**, L141 (2006).

The author declares no competing interests.

Archaeology

Hominins built with wood 476,000 years ago

Annemieke Milks

Understanding the timeline of technological developments sheds light on early societies. A remarkable finding in Africa of a structure made from shaped wood provides clues about our hominin relatives. **See p.107**

The archaeological record is biased against the preservation of organic materials. For no period is this more true than for the Pleistocene epoch, spanning roughly 2.6 million to 11,600 ago. This period provides only isolated examples of early evidence of hominin ancestors using wood or other plant materials. On page 107, Barham *et al.*[1] present their discoveries of modified wood from Kalambo Falls in Zambia. These include the earliest-known example of a hominin-crafted wooden structure, as well as a collection of wooden tools.

Archaeologists' understanding of the use of wood as a raw material during the course of hominin evolution is limited to samples from archaeological sites that have exceptional preservation – usually through either extremely arid conditions or waterlogged sites that lack oxygen. From the Middle Pleistocene (around 774,000 to 129,000 years ago), wooden tools, such as complete spears, have been found at Eurasian sites, including at Clacton-on-Sea, UK, from around 400,000 years ago[2] and at Schöningen in Germany from around 300,000 years ago[3]. Evidence of wood use from this period in Africa is more limited. The other subject of this research is one for which scientists have even less information: to what extent did Mid-Pleistocene hominins structure their environments, if they did at all.

Kalambo Falls, a Middle Pleistocene site, was

Figure 1 | The oldest-known modified wood. a, Barham *et al.*[1] report the discovery in Zambia of 476,000-year-old wood in the form of two logs that were shaped to interlock together around a notch. **b**, Regions of the wood adjacent to the interlocking part, such as this one, show signs of deliberate tool marks (arrows). (Adapted from Fig. 3 and Extended Data Fig. 3 of ref. 1.)

first excavated during the 1950s and 1960s. The earliest layers from these first excavations yielded some wooden finds[4]. Yet, although their size and shape suggested that they were wooden tools, clear signs of manufacturing and use had been erased, possibly by the river. Therefore, although the site was known for its possible wooden tools, little else could be deduced about their use.

Remains of modified wood from at least two distinct phases of hominin occupation were discovered during the excavations reported by Barham and colleagues[1]. From the earlier phase, dated to about 476,000 years ago, the authors describe evidence of the use of wood to form a structure consisting of two interlocking logs (Fig. 1a), the upper segment of which was worked to fit over an underlying trunk. The second phase, dated to between 390,000 and 324,000 years ago, provided evidence of smaller wooden artefacts, including a wedge and a digging stick.

When did our human relatives begin crafting structures as a means of adapting to their environments? In theory, this could have been early in their evolutionary story. Animals routinely engage in 'architecture', including the construction of wooden structures such as nests and beaver dams. Yet, examples of hominin-made structures from the Pleistocene are rare[5], and evidence of the modification of structural elements is rarer still. Around 176,500 years ago in Bruniquel Cave in France, Neanderthals wrenched stalagmites from the ground and used them to craft enigmatic circular structures deep underground[6]. From around the same period, at La Cotte de St Brelade on the island of Jersey, UK, Neanderthals structured their space by stacking piles of mammoth skulls and other bones along one edge of a ravine[7]. Notably, stalagmites and bones are much more likely to survive than wood is.

Although the earliest Kalambo Falls structural elements reported by Barham and colleagues are simple, the authors provide images of wood bearing traces that indicate modification. Tool marks (Fig. 1b) on both logs, as well as the shaping of the upper log, mean that it is improbable that they drifted together naturally.

Similarly, the individuals at Kalambo Falls did not just drag two unmodified logs into the same place, such as might be done to build a nest. Rather, the modifications and visible tool marks suggest that the individuals shaped the top log to fit together with the bottom one, creating a single interlocking structure. The use of tools to make other tools is a behaviour that is characteristic of the genus *Homo*. For example, although chimpanzees (*Pan troglodytes*) sharpen branches to craft hunting aids, they use their teeth[8], instead of tools, to shape the points.

Although Barham and colleagues are rightly cautious about the function of the interconnected logs, they propose a few possibilities to consider, including a walkway, a raised platform or a habitation structure. Whatever the purpose of such a structure, in what would have been a wet environment, the Kalambo Falls hominins seem to have altered their inhabited space in fundamental ways.

Although some amazing discoveries of prehistoric wooden tools have been made, there are notable problems to overcome in terms of studying these artefacts. Traces of manufacture are often on a microscopic scale, which, alongside excavation and conservation challenges, mean that capturing original shapes and traces on wooden items can be a race against time.

Tool marks on wood are highly prone to erasure during manufacture, use, burial and after archaeological excavation, so it was with great foresight that Barham and colleagues captured high-quality photographs in the field. Indeed, tool marks that were clearly visible in photographs became subsequently blurred (see Extended Data Fig. 3 of ref. 1). Without the excavation images, it would have been nearly impossible to confidently distinguish natural wood from modified objects.

In addition to good field recording, modern imaging techniques also help in recognizing and analysing early woodworking, and Barham *et al.* included photogrammetry and scanning electron microscopy methods as part of their analytical toolkit. For future studies, the use of micro-computed tomography scans could offer another method to assess internal anatomical features and shaping strategies, and 3D microscopy could provide a way to analyse surface traces, including tool marks and other traces introduced after burial and excavation. Various types of molecular analyses – such as spectroscopy – and chemical analyses might also be useful in determining whether there are any hallmarks of fire or signs of residues of interest.

Wood remains a key resource in the modern world. Although some tree species are rare, wood can be a sustainable resource when well managed. Its prevalence in contemporary societies, both for construction purposes and for use as tools, contrasts with the rarity of its preservation from the deep past. We are undoubtedly limited by the quality of the archaeological record, with the vast majority of ancient material culture made from wood belonging only to the realm of speculation. Studies such as this one highlight the role of this most humble of materials in the human story, and simultaneously reveal when people started to structurally alter the planet for their own benefit.

Annemieke Milks is in the Department of Archaeology, University of Reading, Reading RG6 6AB, UK.
e-mail: a.g.milks@reading.ac.uk

1. Barham. L. *et al. Nature* **622**, 107–111 (2023).
2. Warren, S. H. *Quart. J. Geol. Soc. London.* **67**, XCIX (1911).
3. Thieme, H. *Nature* **385**, 807–810 (1997).
4. Clark, J. D. (ed.) *Kalambo Falls Prehistoric Site: Volume III, The Earlier Cultures: Middle and Earlier Stone Age* (Cambridge Univ. Press, 2001).
5. Chu, W. *World Archaeol.* **41**, 348–362 (2009).
6. Jaubert, J. *et al. Nature* **534**, 111–114 (2016).
7. Shaw, A., Scott, B. & Pope, M. in *Repeopling La Manche: New Perspectives on Neanderthal Archaeology and Landscapes from La Cotte de St Brelade* (eds Allen, M. J. & Gardiner, J.) Ch. 4 (Oxbow Books, 2023).
8. Pruetz, J. D. & Bertolani, P. *Curr. Biol.* **17**, 412–417 (2007).

Condensed-matter physics

The twisted material that splits the electron

Cécile Repellin

Layers of a thin semiconductor material overlap in a particular pattern, giving rise to particle currents carrying a fraction of the charge of an electron — with potential for encoding quantum information. **See p.63, p.69 & p.74**

The search for new particles is typically associated with enormous underground particle colliders. But it can also be undertaken in a normal laboratory, by studying solids that have been cooled to extremely low temperatures. The complexity of interactions between the myriad electrons in these solids gives rise to intriguing phenomena, such as the fractional quantum Hall effect, in which a large magnetic field can make the electrons in a 2D material behave as though they have been split into three (or more) new particles. These peculiar particles, termed anyons, could be useful for quantum computing, but the magnetic field requirement is impractical. In three papers in *Nature* Cai *et al.*[1] (page 63), Zeng *et al.*[2] (page 69) and Park *et al.*[3] (page 74), and a fourth at *Physical Review X*, Xu *et al.*[4] report observations of the fractional quantum Hall effect in the absence of a magnetic field.

In most solids, electrons move so fast that their repulsion from one another affects their behaviour only minimally. The first condition for observing the fractional quantum Hall effect involves slowing down electrons until their repulsion dominates their behaviour. This feat is possible in a class of material called moiré materials, which are made by stacking thin layers of atoms together, and then twisting each layer relative to the next by a small angle (Fig. 1). The overlapped atomic lattices then create an interference pattern of alternating light and dark patches. An individual layer can be a single plane of carbon atoms (graphene), for example, or it can be a thin semiconductor, such as molybdenum ditelluride (MoTe$_2$; Mo, molybdenum; Te, tellurium), which belongs to the class of material known as transition metal dichalcogenides.

To observe the fractional quantum Hall effect, not only do electrons have to be slow but they also have to have topological properties[5,6]. This mathematical concept has a concrete physical meaning in this context: when a current flows through the material, an electrical resistance appears not only along the current, as is normally the case, but also in a direction perpendicular to it. This variant of the Hall effect occurs in the absence of a magnetic field thanks to the intrinsic properties of the material. For this reason, it is known as the fractional quantum anomalous Hall effect (FQAHE), and a material with this property is called a fractional Chern insulator. But the FQAHE requires a third condition that is even more subtle than the first two — the topological properties need to be somewhat uniformly distributed between the electrons that make up the electrical current.

Finding the three necessary ingredients for the FQAHE in the same material has been a considerable challenge. Twisted bilayer graphene was the subject of frenzied research when moiré materials were first discovered, and it was a strong candidate for the FQAHE, but the fractional quantum Hall effect in this material still requires a small magnetic field[7]. This suggests that twisted bilayer graphene lacks the third ingredient for FQAHE — its topology is not uniform enough. To solve this challenge, the authors of the four studies tapped into the large family of twisted transition metal dichalcogenides.

For the moiré slowdown to happen in MoTe$_2$, the two layers must be misaligned by an angle of 3–4 degrees. When this is achieved, a current emerges at the edge of the sample, carrying charges that each have exactly one-third of the charge of one electron. But fabricating a high-quality MoTe$_2$ sample with such a small twist angle first requires a substantial experimental effort. Once they had managed it, the authors of the four studies used various techniques to observe the FQAHE. Cai *et al.* and Zeng *et al.* probed the material's electronic properties with light, and showed that they

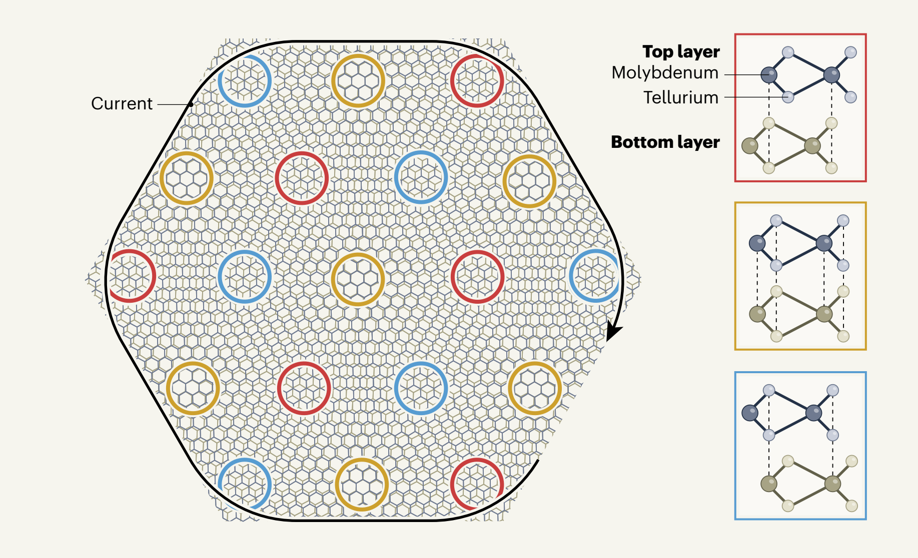

Figure 1 | Edge currents arising in twisted layers. In single-layer molybdenum ditelluride (MoTe$_2$), molybdenum and tellurium atoms are arranged in a hexagonal lattice. When two layers of MoTe$_2$ are stacked on top of one another and twisted relative to each other with a small angle, a moiré pattern emerges, resulting in dark and light patches where different atoms are stacked on top of each other. Under certain conditions, this results in a phenomenon known as the fractional quantum anomalous Hall effect, in which a current emerges at the edge of the material, carrying particles that each have one-third of the charge of one electron. Cai *et al.*[1], Zeng *et al.*[2], Park *et al.*[3] and Xu *et al.*[4] all found evidence for this effect in twisted MoTe$_2$.