other than are those in SDSS J0749+2255. Confirming that such close pairs existed at cosmic noon is particularly useful for understanding how long the final stages of merging and coalescence took during this period. For SDSS J0749+2255, the authors estimated this duration to be hundreds of millions of years.

Detailed multi-instrument studies such as that of Chen and colleagues are particularly welcome in the current era of 'multi-messenger' astrophysics, in which discoveries are made using observations from several sources. One such source will come from the gravitational waves that supermassive black holes produce when they finally merge, and that will be detectable with the Laser Interferometer Space Antenna[8] and Pulsar Timing Arrays[9,10] that are under construction. It is crucial that the black holes that generate these waves are characterized at all evolutionary stages so that the detections can be interpreted properly. Similarly, the rate at which these waves are generated, which will also soon be measurable, will directly test current astrophysical models, potentially revolutionizing what is known about the formation and evolution of supermassive black holes.

Forthcoming surveys with the Vera C. Rubin Observatory in Chile and the Square Kilometre Array in Australia and South Africa will offer a better depth and sky coverage than is possible with current telescopes. These surveys will allow the detection of supermassive black holes with a range of masses that are at various phases of galaxy merger, and at all cosmological distances. However, as long as these systems are observed only in a single survey (covering a limited band of frequencies), they will remain candidate dual AGNs, rather than confirmed pairs. Chen *et al.* have defined a clear method for confirming these candidates. And although the authors' approach is observationally expensive, it shows that sharp multi-wavelength observations are indispensable for understanding galaxy formation.

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1. Begelman, M. C., Blandford, R. D. & Rees, M. J. *Nature* **287**, 307–309 (1980).
2. Chen, Y.-C. *et al. Nature* **616**, 45–49 (2023).
3. Ghez, A. M., Morris, M., Becklin, E. E., Tanner, A. & Kremenek, T. *Nature* **407**, 349–351 (2000).
4. Padovani, P. *et al. Astron. Astrophys. Rev.* **25**, 2 (2017).
5. Volonteri, M., Habouzit, M. & Colpi, M. *Nature Rev. Phys.* **3**, 732–743 (2021).
6. Di Matteo, T., Springel, V. & Hernquist, L. *Nature* **433**, 604–607 (2005).
7. De Rosa, A. *et al. New Astron. Rev.* **86**, 101525 (2019).
8. Colpi, M. *Space Sci. Rev.* **183**, 189–221 (2014).
9. Burke-Spolaor, S. *et al. Astron. Astrophys. Rev.* **27**, 5 (2019).
10. Mingarelli, C. M. F. *Nature Astron.* **3**, 8–10 (2019).

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Forum: Climate change

The medieval Moon unveils volcanic secrets

Innovative use of medieval musings about the Moon has revealed that volcanic eruptions coincided with abrupt, global-scale cooling events. The approach is exciting from the perspective of climate scientists and historians alike. **See p.90**

The paper in brief

- **Volcanic eruptions inject large volumes of sulfur dioxide into the atmosphere that are converted into aerosols in the stratosphere[1].**
- **These aerosols produce volcanic dust that can reduce incoming solar radiation, altering Earth's surface temperatures, precipitation and atmospheric circulation[2].**
- **Identifying past volcanic eruptions can therefore help to clarify the timing and nature of climate events, but current methods produce conflicting results.**
- **On page 90, Guillet *et al.*[3] report an approach that interprets medieval accounts of lunar eclipses to date volcanic eruptions that could have shaped a key climatic transition.**

Andrea Seim & Eduardo Zorita

A fresh take on an old challenge

Climate scientists usually identify past volcanic eruptions by measuring the acidity and amount of volcanic ash in cores drilled from polar ice, or by inferring abrupt temperature changes in tree-ring records. However, these sources sometimes disagree, because the location, intensity and timing of eruptions can produce varying results, as can circulation of the atmosphere. Guillet and colleagues' approach offers an independent — and perhaps even more direct — source of information about the timing of volcanic eruptions, which could resolve some of these disagreements.

> **"Dark lunar eclipses were observable for 3–20 months after an eruption."**

During a total lunar eclipse, the Moon is fully in Earth's shadow. A dark Moon indicates that volcanic aerosols are highly abundant in the stratosphere, whereas a reddish Moon suggests that they are scarce (Fig. 1). Guillet *et al.* examined historical accounts of lunar eclipses from the High Medieval Period (1100–1300), and estimated the abundance of volcanic aerosols from the descriptions of the colour and luminosity of the Moon. They used this information to refine the timing of a cluster of volcanic eruptions that occurred during this period, and which had previously been identified using ice-core measurements[4]. The authors found that seven of these eruptions generated aerosols that could have had a role in the transition from the Medieval Climate Anomaly (around 850–1250) to the Little Ice Age (around 1300–1850).

The strength of Guillet and co-workers' study lies in the precision with which the authors estimated the timing of volcanic eruptions — pinpointing the year, and even in some cases the month, of the event. The authors compared their findings with modern global aerosol measurements, climate model simulations and satellite observations to link five dark and two reddish lunar eclipses to major eruptions during the High Medieval Period. They found that the dark lunar eclipses were observable for 3–20 months after an eruption.

They then examined tree-ring records sensitive to summer temperatures in the Northern Hemisphere, in which an unusually cold summer is indicated by reduced wood formation. By combining these records with climate simulations, the authors further refined the timing of five eruptions and showed that they had a pronounced impact on the climate. The remaining eruptions

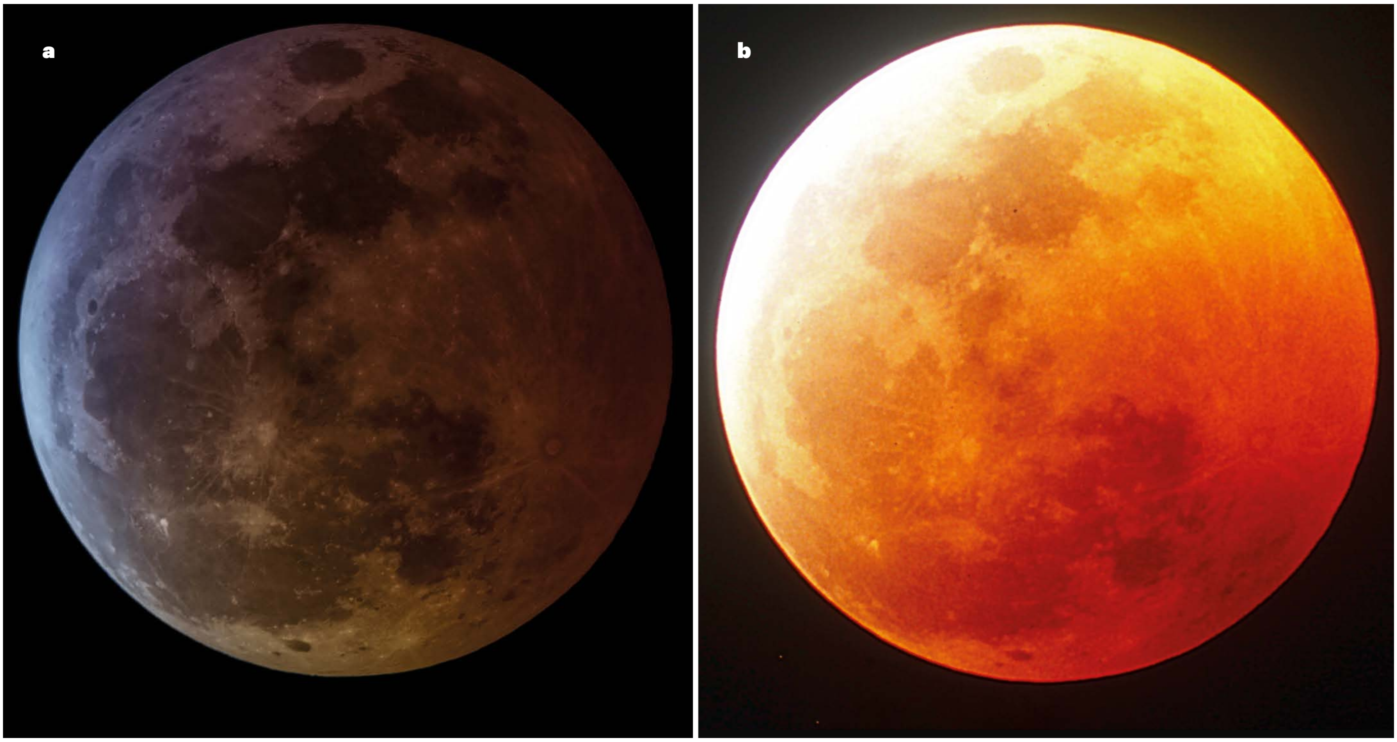

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Figure 1 | The colours of total lunar eclipses. a, A dark Moon during a lunar eclipse indicates that Earth's stratosphere contains a large amount of volcanic aerosols. This photograph was taken in January 2019, roughly one month after the eruption of Anak Krakatau in Indonesia. **b**, A bright reddish Moon suggests that volcanic aerosols are scarce, as shown in this photograph from January 2001. Guillet *et al.*[3] used historical accounts of the colours of lunar eclipses to infer the climatic impact of volcanic eruptions in the High Medieval Period (1100–1300).

seem to have had less effect.

Guillet and colleagues' findings will improve our understanding of how much volcanic eruptions contributed to the onset of the Little Ice Age compared with other factors, including a period of low solar activity between 1280 and 1340. Climate models suggest that a volcano-induced cooling in surface temperatures can lower ocean temperatures and expand sea ice[5]. This can, in turn, stretch the effects of a volcano over several decades, and could even plunge the climate system into a different state – a prospect that has relevance for modern warming as a result of anthropogenic greenhouse-gas emissions. Although the climatic changes caused by volcanic and anthropogenic emissions differ, understanding how the climate system reacts to different types of perturbation will also help to refine the next generation of climate models[6]. And getting the timing right is crucial, which is why innovative approaches such as that of Guillet and colleagues are so valuable.

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Anne Lawrence-Mathers
Making sense of historical records

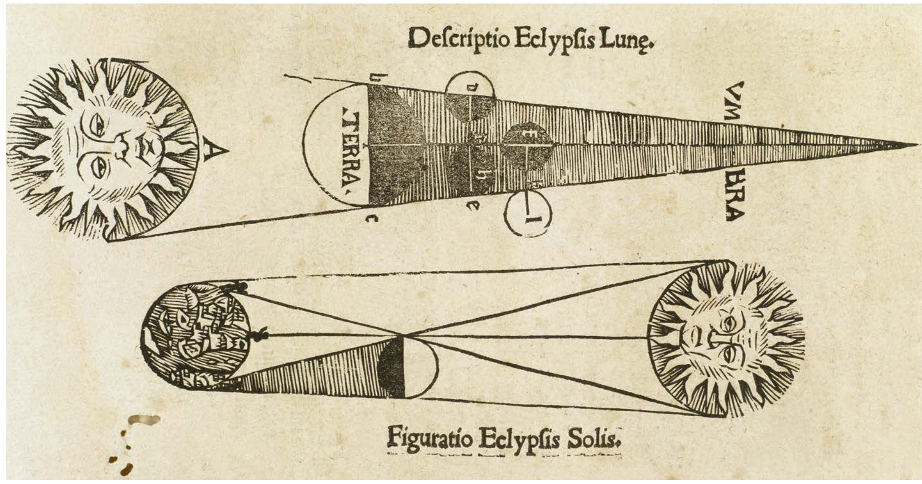
Guillet and colleagues' findings are underpinned by hundreds of records chronicling 187 lunar eclipses between 1100 and 1300. Their approach to linking these events to the climatic impact of volcanic eruptions hinges on descriptions of the colour of the Moon. Such information is scarce in these records, except in Christian sources, in which the colour and brightness of the Moon is documented in 36 of the eclipses studied. But the authors faced difficulties in dating these eclipses because the sources are not always consistent – a challenge related to medieval church bureaucracy.

In the medieval Christian world, lunar phases and eclipses were used for setting the dates of religious festivals and timing medical treatments – or for determining whether a darkened Moon was a sign from God. New astronomical tools and theories were therefore valued highly. Calculating the lunar calendar accurately was important to Christians because the Moon touched on so many of their activities.

Such studies certainly became more accurate when Latin translations of Islamic astronomical texts and planetary tables were made available in Europe from around 1150 (ref. 7). However, these texts used an entirely different calendar and referenced dates that were meaningful only for their original compilers. They also described astronomical observations that were made far from northern Europe. Early translations were literal and offered little help to users unfamiliar with the Islamic calendar.

The resulting struggles are clear in the writings of a monk known as John, who chronicled sunspots and a solar eclipse from his post at Worcester Cathedral in England at the start of the High Medieval Period. John made detailed records of these astronomical phenomena, but still failed to understand the Islamic methods for calculating lunar eclipses[8,9]. Nevertheless, the planetary tables were valued, and – once more-sophisticated translations and recalculations had been produced – they formed the basis of textbooks on astronomy. One such book was written by Johannes de Sacrobosco in around 1220, and immediately became widely used (Fig. 2). How, then, could there be continuing doubts about the timing and identification of lunar eclipses?

Central to the answer is the fact that the solar year did not align exactly with a year in the Julian calendar. Sacrobosco argued that the accumulated error had reached some 11 days by around 1230 and that Easter was therefore being celebrated on the wrong day[10]. Church leaders were aware of the problem, but feared there would be serious resistance to changing the calendar[11]. The timing of phases



PRIMA ARCHIVO/ALAMY

Figure 2 | A diagram of solar and lunar eclipses, from a printed edition of Johannes de Sacrobosco's astronomical text (around 1220).

of the Moon was therefore out of step with the calendars of major religious institutions.

Church chroniclers faced a dilemma. Some saw a darkening of the Moon as a clear sign of an eclipse, whereas others interpreted it differently. The problem was exacerbated by the fact that a given eclipse might be more clearly visible in some parts of Europe than others, and that information took time to be transmitted between regions. For these reasons, the lack of agreement between medieval chroniclers on the timing of total eclipses of the Moon should not be seen as the result of religious censorship or ignorance — they were simply days out of sync. In this context, Guillet and co-workers' accomplishment in overcoming this problem to link historical sources to climate events is all the more impressive.

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1. Rampino, M. R. & Self, S. *Nature* **310**, 677–679 (1984).
2. Robock, A. *Rev. Geophys.* **38**, 191–219 (2000).
3. Guillet, S. *et al. Nature* **616**, 90–95 (2023).
4. Sigl, M. *et al. Nature* **523**, 543–549 (2015).
5. Miller, G. H. *et al. Geophys. Res. Lett.* **39**, L02708 (2012).
6. Merlis, T. M., Held, I. M., Stenchikov, G. L., Zeng, F. & Horowitz, L. W. *J. Clim.* **27**, 7781–7795 (2014).
7. Al-Khalili, J. *Pathfinders: The Golden Age of Arabic Science* 67–78 (Lane, 2010).
8. Nothaft, C. P. E. *Early Sci. Med.* **20**, 187–208 (2015).
9. Lawrence-Mathers, A. E. *J. Mediev. Hist.* **39**, 255–274 (2013).
10. Moreton, J. *Viator* **25**, 229–244 (1994).
11. Nothaft, C. P. E. *Scandalous Error: Calendar Reform and Calendrical Astronomy in Medieval Europe* (Oxford Univ. Press, 2018).

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From the archive

The wonders of life contained in the soil beneath our feet, and the sociability of cats.

100 years ago

The number of organisms in one single gram of soil — no more than a teaspoonful — often well exceeds 40 millions. This looks big, but it is difficult to form an idea of its immensity. If each unit in the whole array could be magnified up to the size of a man and the whole caused to march past in single file, they would go in a steady stream, every hour of the day and night for a year, a month and a day, before they had all passed. We must think then of the apparently lifeless soil which we tread beneath our feet as really throbbing with life, changing daily and hourly in obedience to some great laws which we have not yet discovered; pulsating with birth, death, decay, and new birth. And if the wonder were not sufficient, we know that in some way these lowly organisms are preparing the food for our crops ... It is possible ... that our attempts to learn something of this wonderful population may lead to some degree of control which would have valuable economic results. But even if this never happened the work would still be justified because it shows to the countryman something of the abounding interest of his daily task and of the infinite wonder of the soil on which he spends his life.
From *Nature* 7 April 1923

150 years ago

It may prove of interest to naturalists to record the following curious instance of the social habits of cats :— I once had two she cats that were upon very intimate terms with each other, always together, and never appeared to have quarrelled. At one time, one of them being about to add an increase to their number, the other very kindly nursed it, and even performed the function of a midwife, and actually attended to the necessary offices that are in ordinary cases attended to by the parent of the progeny. ... I carefully watched my pets, and can therefore vouch for the truthfulness of this extraordinary manifestation of feline sociability.
From *Nature* 3 April 1873

NATURE

Tumour biology

Cancer cells remodelled to resist chemotherapy

Stephanie Panier

Cancers that arise from epithelial cells often contain tumour cells that have acquired the characteristics of another cell type — a mesenchymal cell. A mouse model of skin cancer offers insights into why such cells resist treatment. **See p.168**

Modern therapeutic approaches for cancer, such as 'targeted' drugs or therapies that harness the immune system, have greatly advanced the treatment options for many types of tumour. However, chemotherapy failure is a key limiting factor in treatment success. On page 168, Debaugnies *et al.*[1] provide some reasons for why such treatment resistance can occur.

In cancers that arise from epithelial cells (which line the surfaces of the body), treatment resistance is closely associated with a process called the epithelial–mesenchymal transition (EMT). During EMT, cancer cells of epithelial origin progressively lose their epithelial characteristics and acquire those of another cell type — a mesenchymal cell (Fig. 1). These newly gained characteristics enable the