

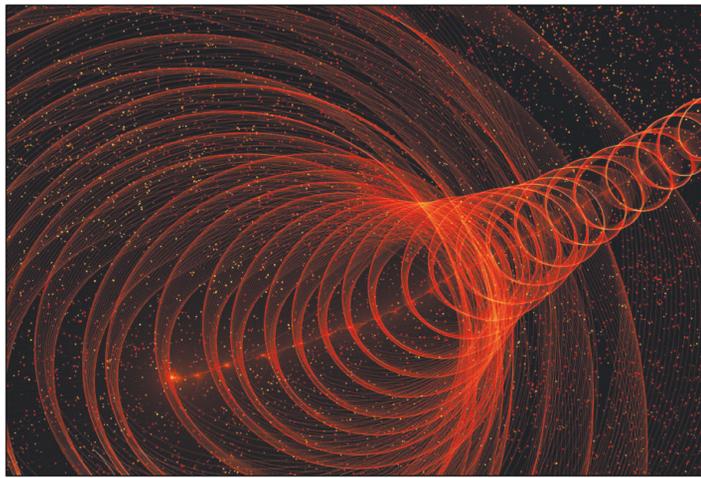
Physicists find electronic agents that govern flat band quantum materials

Quantum Physics

By Rice University

Physicists have directly visualized the fundamental electronic building blocks of flat-band quantum materials, a class of systems in which electron motion is effectively quenched and strong interactions give rise to emergent phases of matter. In a study published in *Nature Physics*, Qimiao Si's group at Rice University, in collaboration with researchers at the Weizmann Institute of Science, identified compact molecular orbitals that act as the key electronic agents governing the exotic behavior of these materials. "In flat band materials, electron motion experiences destructive interference," said Si, the Harry C. and Olga K. Wiess Professor of Physics and Astronomy and director of Rice's Extreme Quantum Materials Alliance.

These flat band materials are also topological with properties that are preserved as the material continuously bends or stretches in any symmetry-preserving way. "The electron motion is subject to a global effect described by the mathematical notion of topology," said Mounica Mahankali, a graduate student and co-first author on this paper. "The electronic states are configured such that when one goes through the space of electron states and returns to the starting point, a non-zero winding number has been acquired." When Si developed a theory that allowed him to ask how the topology affects correlation physics, or the interactions of electrons that determine how electrons are organized in the system, he said he was excited about the new questions it opened into the interplay between topology and correlation



physics. This theory, previously published in *Science Advances*, centers on the quantum critical point, a point of transition in a quantum material which Si believed could be inter-

rogated through compact molecular orbitals, the agents that represent the flat bands in flat band materials. "Think of it like a highway with the right lane experiencing stopped, heavy traffic

and the left lane experiencing free-flowing, fast-moving traffic," Si said. In this scenario, drivers will change lanes, moving to the right in order to prepare for an exit, or moving to the left

to try to avoid traffic. The right lane is a solid, stuck, ordered state; the left lane is fast-moving and liquid. As the cars change lanes, however, the state of the lanes changes too. Eventually, there will be a critical point where each lane could enter into either a traffic-jammed state or a free-moving state, depending on the movement of the cars. By examining the compact molecular orbitals, or the traffic-jammed lane, at this quantum critical point, Si theorized he could learn about the free-moving state. "As appealing as our theory is, it remains a hypothesis until it's proven by experiment," Si said. Si met Haim Beidenkopf, a professor at the Weizmann Institute in Israel, during their joint stay at the Kavli Institute of Theoretical Physics at the University of California, Santa Barbara. Beidenkopf, a quantum experimentalist, specializes

in imaging quantum materials using atomic resolution spectrometers. He was already running an experiment on a flat band material, but the conversation made it clear that his experiment is uniquely suited to test whether the hypothesized compact molecular orbitals actually underlie its exotic physical properties. In the experiment, Beidenkopf used an atomic resolution spectrometer to study a highly correlated metal—a material with highly agitated electrons—called Ni₃In. Ni₃In was selected for its potential practical application, as resolving the mechanism for its unusual electronic properties could provide insights into high temperature superconductivity. "In this study, we combined atomic-scale spectroscopy with material-specific analytical modeling to probe the spatial profile of the current that goes in and out of

the kagome metal Ni₃In," said Beidenkopf, the corresponding author on this study. "By doing so, we have revealed the kagome flat-band origin of the unusual quantum critical behavior in this compound and demonstrate the exquisite spatial profile expected from the compact molecular orbitals that leads to it." The experimental data both confirmed the existence of compact molecular orbitals and, through the application of Si's theory, allowed the researchers to identify the kagome structure that was responsible for the quantum critical state. "This collaboration showed, experimentally, that compact molecular orbitals serve as the agents that underlie the highly agitated quantum critical state of matter," Si said. "This provides new insight into high temperature superconductivity and opens the door for new quantum applications."

Moons orbiting wandering exoplanets could be habitable—with one catch

Planetary Sciences

By Sam Jarman

Provided they host thick, hydrogen-dominated atmospheres, moons orbiting free-floating exoplanets could retain much of the heat generated deep within their interiors by tidal forces. Led by David Dahlbäck at the Max Planck Institute for Extraterrestrial Physics and Giulia Rocchetti at the European Space Agency, a new study predicts that hydrogen could act as a potent greenhouse gas—potentially providing habitable conditions for billions of years after their host planets are first ejected from their stellar systems. The work has been published in *Monthly Notices of the Royal Astronomical Society*. Heat-absorbing hydrogen



Astronomers have now discovered hundreds of exoplanets drifting through interstellar space, most of them likely flung from their parent systems by violent gravitational encounters in the distant past. After ejection, these rogue worlds would likely have become extremely cold and dark—according to some astronomers, their moons may have faced more interesting fates. During the chaos of ejection, a moon's orbit can become highly elongated, causing it to be repeatedly stretched and squeezed by its host planet's gravity. Much like Europa and Enceladus in our own solar system, these tidal forces could generate vast amounts of internal heat. If such a moon's atmosphere were unstable enough for gases to condense into liquid form, most of this tidal heat would simply radiate

into space. But the situation could be very different for high-pressure atmospheres dominated by hydrogen. In Earth's present-day atmosphere, hydrogen molecules (simple pairs of bonded hydrogen atoms) have little warming effect—but under high pressures, they can absorb heat through a process known as "collision-induced absorption" (CIA). During fleeting collisions, hydrogen molecules form supramolecular complexes: temporary assemblies held together by weak, non-covalent bonds. These complexes are far better at absorbing infrared radiation than the bonds within isolated hydrogen molecules and can rival the absorption of potent greenhouse gases like carbon dioxide and methane. As a result, some previous studies have considered how much of the energy generated inside a moon, or even newly formed planets, could be trapped efficiently in a thick hydrogen atmosphere. If this were possible, these atmospheres could heat up without the large-scale condensation that plagued earlier carbon dioxide-dominated models. "Such an exomoon could have surface temperatures sufficient to keep water liquid without a nearby star,

significantly expanding the possibilities for life to emerge in the universe," Dahlbäck explains. "But although such moons could even be detected in the near future, the confirmation and analysis of any atmosphere may well be impossible for a long time." Combining calculations For now, the best way to explore these exotic environments is through modeling. As Dahlbäck explains, these simulations allow researchers to track how a moon's atmosphere and orbit evolve over billions of years following its planet's ejection. "We combined accurate calculations of atmospheric temperatures with feedback on the chemical composition, mainly through condensation," he says. "This results in the most realistic—albeit still approximate—simulations of such moons to date." On top of this, the researchers incorporated the latest theoretical insights into how exomoon orbits change over time. "In 2023, a study led by Giulia Rocchetti modeled how orbital circularization leads to a decrease in the available tidal heat over time," Dahlbäck continues. "Together with these previous results, we can calculate the maximum time spent in the

Ancient sling bullet delivers a 2,100-year-old taunt: 'Learn your lesson!'

ARCHAEOLOGY

By Sandee Oster

For millennia, sling bullets served as a hand-thrown projectile that could be used to fend off enemies. At Hippos, 70 sling bullets made of lead have been recovered over the course of fieldwork and excavation. However, while many are bare or depict scorpions and thunderbolts, one recently recovered sling bullet is the first inscribed example ever recovered at Hippos and the only known sling bullet ever inscribed with the letters MAΘΟΥ meaning "Learn your lesson!" Context of the finds In a study published in *Palestine Exploration Quarterly*, Dr. Eisenberg and his colleagues describe the findings of and decipher the unique description found on a lead sling bullet from Hippos. Antiochia Hippos formed part of the Roman Decapolis, founded after the Battle of Paneion around 199 BCE, before being incorporated into Provincial Syria after Pompey's conquest in 64 BCE. The inscribed sling bullet (B19655) was recovered with the help of a metal detector close to the riverbed of the Sussita Stream in 2025. The streambed would have been an excellent point of attack for besiegers focusing on the city's main gate on the east, especially those with heavy siege machinery. According to Dr. Michael Eisenberg, lead author of the study, "We use metal detectors very frequently next to our excavation areas. Sling bullets are among the easiest to find with a metal



detector due to their lead mass, and so far we have found more than 70 bullets only at Hippos and its surroundings." A unique sling "Sling bullets were a cheap munition, a hand-thrown projectile, used for millennia. Its throwing power is based on swirling a long sling made of rope while the bullet rests in a leather pouch," explained Dr. Eisenberg. "Prehistoric stone and clay bullets were replaced by lead bullets, which were widely used from the Classical period onward. The high relative mass of lead, its relatively low cost, and its low melting point made it ideal for bullet preparation in stone molds, each of which usually holds eight cast bullets. They are usually shaped as an ellipsoid with pointy edges or 'almond-shaped.' They differ in mass and size, from ca. 20 to 55 g., each measuring about 3x2 cm. "At short distances, up to about ca. 100 m, they were highly effective at hitting individual targets, while at longer distances they were effective against a cluster of enemies ... In Greater Syria, where Hippos is part of, most of the lead bullets are dated to around the 2nd century BCE, same as the Hippos one." Upon discovery of the Hip-

pos bullet, the inscription MAΘΟΥ was noted. Sling bullets often have inscriptions upon them, including the names of deities, cities, military units, and acclamations of victory. In some cases, sling bullets may also bear personal names, often relating to the shooter or commander, inscribed on both sides of the bullets. The inscribed Hippos sling bullet was only inscribed on one side, making it unlikely to represent a personal name. Instead, the authors suggest the inscription is more likely to be a form of taunt. Similar taunts have been recovered on other sling bullets bearing inscriptions such as "take a taste," "receive this," or "take it." The Hippos sling bullet would likely have read as μαθου, meaning "Learn your lesson!" The grammatical form used in the inscription of the bullet (Greek middle-voice) would intensify the mockery, Dr. Eisenberg explained. "The reading of the sole word in Greek on the bullet is made with a very high degree of confidence, as it is clear and does not miss any letters. "Its interpretation took more time as it is the only instance in which such a word appears on a bullet and its imperative in the middle voice, which could make the case even more

sarcastic—the bullet is telling itself to learn and hit the enemy well. Discover the latest in science, tech, and space with over 100,000 subscribers who rely on Phys.org for daily insights. Sign up for our free newsletter and get updates on breakthroughs, innovations, and research that matter—daily or weekly. "Lead, in general, and the bullets in particular, hardly suffer any time erosion. They just get patinated, and such cases are cleaned gently in the conservation lab. As they are rather soft and are thrown at high power, they seldom bear impact scars or even miss a part of the bullet. Such a scar is evident on the present bullet, a testimony to its use." The Hippos' inscribed sling bullet was most likely hurled from the city defenders located on the city walls at enemy forces below. Hippos was the site of many battles during the Hellenistic period; however, which battle in particular this bullet belonged to is uncertain. Among the battles fought at Hippos were a battle that occurred before the city's establishment during Ptolemaic rule, the Battle of Paneion in ~199 BCE, an attempted conquest in ~101 BCE by Alexander Jannaeus, and the city's eventual conquest in ~83 BCE.

Satellite radar shows Alaska glaciers melt three extra weeks for each 1°C of summer warming

ENVIRONMENT

By Rod Boyce

Alaska's glaciers respond to climate change by melting for three additional weeks with every 1 degree Celsius increase in the average summer temperature, data from satellite-mounted radars show. A single degree Celsius equates to 1.8 degrees Fahrenheit. Work by scientists at Carnegie Mellon University and the University of Alaska Fairbanks also shows that synthetic aperture radar, or SAR, can consistently and automatically monitor glaciers and their snowlines year-round. Those are usually only gauged at the end of the melt season using optical instruments. SAR data is also more reliable than traditional surface-based optical instruments. The findings were published Feb. 4 in *npj Climate and Atmospheric Science*. The lead author is recent Ph.D. graduate Albin Wells of Carnegie Mellon University. Co-authors are assistant professor David Rounce of Carnegie Mellon and Mark Fahne-

stock of the UAF Geophysical Institute. Rounce previously was a Geophysical Institute postdoctoral fellow and research associate. The scientists used the radar data to track the number of glacier "melt days." A single melt day can be one 24-hour period in which an entire glacier is melting, or it can consist of multiple days where portions of the glacier melt and eventually reach the glacier's total surface area equivalent. An increase in melt days over time signals a longer melt season and accelerates a glacier's net loss of ice. Using European Sentinel-1 radar satellite data, the researchers tracked changes throughout each melt season at nearly all Alaska glaciers larger than about half a square mile from mid-2016 through 2024. Synthetic aperture radar works by sending microwave pulses toward the ground from a moving aircraft or satellite and combining the returning echoes to create detailed images, even through clouds and in darkness. Sentinel-1 passes over the



same location every 12 days, covering more than 3,000 Alaska glaciers. The team also found that short-term heat waves caused Alaska's glaciers to lose up to 28% more of their protective snow cover than in typical years. That percentage is at the scale of individual mountain ranges rather than applying uniformly to each glacier within a mountain range.

"Our ability to quantify these changes is really important," Wells said. "Melt extents and snowlines are proxies for glacier mass balance." Glacier mass balance is the difference between how much snow and ice a glacier gains and how much it loses over time. "These correlations with temperature begin to give a sense for how much melt or snow-

line retreat we can anticipate under future, warmer climates across the region," Wells said. The snowline marks the division between a glacier's accumulation zone, where snow builds up and adds mass, and its ablation zone, where melting removes snow and ice. Glaciologists typically use optical equipment to assess snowlines at the end of the melt season, usually in late

summer or early fall. "In optical data, the snowline can be really hard to observe," Fahnestock said. "If you're a day late taking your picture, it might have snowed on the entire glacier, and you can't see where the bare glacier ice is down below and where the snow and firn is above." Firn is partially compacted granular snow that forms the surface part of the upper end of a glacier and can eventually become ice. Fahnestock noted that optical instruments can be affected by variable lighting conditions, shading, clouds, and whether firn is clean or dirty. SAR overcomes that and can also provide regular in-season snowline updates. "What Albin has done is operationalize the tracking of surface conditions on the glaciers in a way that can be applied anywhere," Fahnestock said. The research paid close attention to a June 23–July 10, 2019, Alaska heat wave that encompassed all glaciated regions of Alaska except the Brooks Range. Temperatures rose to 20 to 30 degrees above average at many locations for nearly two weeks. Several days set all-

time records, including 90 degrees Fahrenheit at Ted Stevens Anchorage International Airport. Anchorage's typical summer highs are in the mid-60s. The excessive heat caused glacier snowlines to retreat nearly 350 feet in elevation, according to the researchers. Snowlines do not retreat that high in a typical year until about two months later. The change lengthened exposure of bare ice and firn, leading to increased mass loss. The authors write that this underscores "the sensitivity of glaciers to short-term climatic variability." Wells said the research also revealed consistent differences in the number of melt days between glaciers on the coastal side of mountain ranges and those farther inland. The pattern suggests the glaciers operate differently even though many are losing ice at broadly similar rates. "This is an important finding," Wells said, "because it corroborates prior knowledge that glaciers in Alaska on the coastal side of mountains have more melt in summer and more accumulation in winter than those on the continental side of the ranges."