current-affairs programme. The response was beyond anyone's wildest dreams. Within a few days, volunteers were classifying 70,000 galaxies every hour on their own computers.

One of Lintott's key messages is that citizen science is much more than free labour. Many such projects exploit the human brain's ability to recognize patterns, or to spot unusual features in data that even the most sophisticated computer algorithms can miss. Collaborations between professional and amateur researchers also increase public understanding of science, and have produced a growing list of publications in peer-reviewed journals. The first Galaxy Zoo paper, released in 2008, has been cited in more than 500 other astronomy papers (C. J. Lintott *et al.* Preprint at https://arxiv.org/abs/0804.4483; 2008). Reef Life Survey, a citizen-science project that engages recreational divers around the world to monitor biodiversity in coral reefs, has produced nearly 60 peer-reviewed papers so far, including 5 in this journal.

Citizen scientists have also made serendipitous discoveries on their own. In 2007, for example, Dutch school teacher Hanny van Arkel stumbled upon a mysterious green blob in an image she was examining for Galaxy Zoo. This unusual object, which became known as Hanny's Voorwerp (Dutch for 'Hanny's thingy'), is now thought to be a giant cloud of gas illuminated by a powerful blast from a supermassive black hole in the neighbouring galaxy IC 2497.

Zooniverse, as Lintott shows, hugely expands the field of investigation. Penguin Watch, for example, invites volunteers to monitor the rise and fall of Antarctic penguin populations by counting birds photographed by a network of automated cameras. Snapshot Serengeti uses a similar approach to study animal ecosystems revealed by millions of photographs taken with motion-sensitive cameras throughout Tanzania's Serengeti National Park. The Space Warps project invites armchair astronomers to search for rare but spectacular gravitational lenses, created when gravity distorts images of faraway galaxies. These act like enormous funhouse mirrors to produce optical illusions on the grandest scale.

Lintott is not the first to write about this topic. Caren Cooper's 2016 *Citizen Science*, for example, was illuminating. However, it is hard to imagine anyone more qualified than Lintott — a veteran of the citizen-science trenches — to give an insightful perspective. And he does so both accessibly and engagingly. There is a flavour of Bill Bryson's breezy erudition in *A Short History of Nearly Everything* (2003), although the book does ramble in places. Overall, however, Lintott deftly interweaves personal experience and more philosophical ruminations on public participation in science.

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What of the future of citizen science? Astronomy, once photon-starved, will soon be awash in 15–30 terabytes of new data nightly from the Large Synoptic Survey Telescope in northern Chile, triggering myriad follow-up observations. Other fields face similar challenges coping with an ever-faster flow of data. Genomic researchers are both blessed and burdened by a deluge of data emanating from hugely accelerated sequencing. And remote-sensing observations by a growing armada of satellites, such as the joint European–Japanese EarthCARE mission scheduled for launch in 2021, will map and measure our planet's surface as never before over the next decade. Although increasingly powerful computers and artificial intelligence can help to analyse the data tsunamis, they won't make citizen scientists obsolete any time soon.

Scrutinizing Earth's surface is one thing; having an impact on the future of the planet and its people is another. Can citizen science change the world? Maybe. From monitoring flower production by plants as a gauge of climate change to analysing brain scans in the quest to find the cause of Alzheimer's disease, lay researchers are actively improving lives globally. Just days after Hurricane Dorian devastated the Bahamas in late August, a new Zooniverse project was already helping rescue efforts as volunteers identified damage visible in satellite images.

Moreover, as Lintott reminds us, this great public venture is helping to foster a more scientifically literate society, and empowering a new generation of scientists. Not bad for a free app that you can download to your phone. ■

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CHEMISTRY

From bomb to Moon

Angela N. H. Creager is inspired by the life of the Nobel laureate who discovered deuterium.

After witnessing the 1945 Trinity atomic-bomb test, the theoretical physicist J. Robert Oppenheimer recalled Hindu scripture: "Now I am become Death, the destroyer of worlds." Although this is often interpreted as admitting moral culpability on the part of the Manhattan Project's scientific director, Oppenheimer remained a central player in the nuclear-weapons establishment until he lost his security clearance in the mid-1950s.

Harold Urey also worked for the Manhattan Project. But by contrast, the Nobel-prizewinning chemist distanced himself from nuclear weapons development after the war. His search for science beyond defence work prompted a shift into studying the origins of life and lunar geology. Now, the absorbing biography *The Life and Science of Harold C. Urey* by science historian Matthew Shindell uses the researcher's life to show how a conscientious chemist navigated the cold war.

Shindell argues that Urey's pious upbringing underpinned his convictions about the dangers of a nuclear arms race, and his commitment to research integrity. Urey grew up a minister's son in a poor Indiana farming family belonging to a plain-living Protestant sect, the Church of the Brethren. Progressing through increasingly diverse educational environments, culminating in a PhD at the University of California, Berkeley, Urey became self-conscious about the zealousness of his family's faith. He also found the path to a cosmopolitan, middle-class life.

In the 1920s, Urey was among a small group of chemists who collaborated closely with physicists. Working at Niels Bohr's

Institute for Theoretical Physics at the University of Copenhagen, he kept abreast of developments in quantum mechanics. There, and on travels in Germany, he met the likes of Werner Heisenberg, Wolfgang Pauli and Albert Einstein. But Urey decided he lacked the mathematical skills to make theoretical advances in quantum chemistry. Moving back to the United States, he started both a family and an academic career.

At Johns Hopkins University in Baltimore, Maryland, and later at Columbia University in New York City, Urey taught quantum mechanics to chemists, while setting out on the trail that led him to deuterium. In 1931, he discovered this isotope of hydrogen. Predicted on the basis of work by Bohr, Frederick Soddy, and J. J. Thomson, its existence had been doubted by many chemists and physicists. Urey's identification won him the Nobel three years later. By this time, he had also co-authored one of the first texts in English on quantum mechanics as applied to molecular systems, the 1930 *Atoms, Quanta and Molecules*.

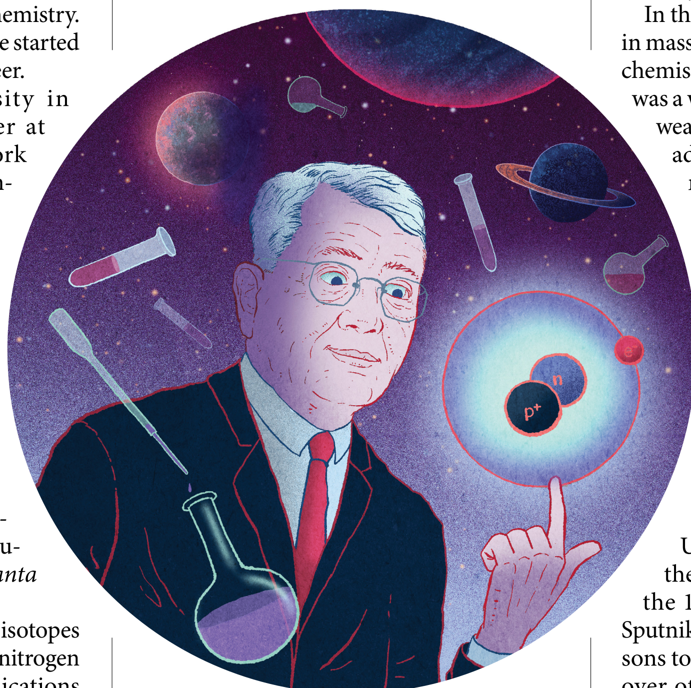
Urey's continuing work on stable isotopes of other chemical elements, such as nitrogen and oxygen, led to important applications in biochemistry and geochemistry, including the pioneering use of isotopic labels to study metabolic pathways. Living in New York also led Urey to political liberalism. He became aware of the anti-Semitism affecting Jewish scientists, and the lack of opportunities for women scientists. A generous mentor, he shared his Nobel prize money with two collaborators, and split a grant he had been awarded with the young Isidor Rabi (who later discovered nuclear magnetic resonance).

MANHATTAN TRANSFER

The Second World War changed Urey's life, as it did those of most physical scientists and researchers in many countries. His expertise in isotopes made him valuable to the Manhattan Project. Here, he eventually headed a massive team of scientists and engineers working on the separation of uranium isotopes using gaseous diffusion methods. However, he was ill-suited to the pressure of managing this technologically complex and cumbersome project, and Leslie Groves — the project's overall director — regarded him with suspicion. Even before the war's end, Urey became deeply disenchanted with working for the military.

After the war, Urey used his laureate status to voice alarm about the prospect of nuclear warfare. He backed international control through world government as a way to control the military future of atomic energy. This was not a radical view in 1946; it was advanced in the US government's Report on the International Control of Atomic Energy, much of which had been drafted by Oppenheimer.

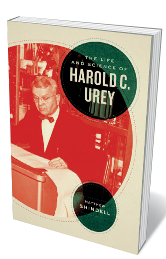
However, when the Soviet Union refused this plan for international control, which



AFTER THE WAR, UREY USED HIS LAUREATE STATUS TO **VOICE ALARM** ABOUT THE PROSPECT OF NUCLEAR **WARFARE.**

preserved the US atomic monopoly, advocates of world government found their loyalty as citizens questioned. In 1946, Urey was attacked by J. Parnell Thomas (who would go on to head the House Un-American Activities Committee) for being "one-world-minded", and not sufficiently patriotic. The FBI also investigated Urey, claiming that he belonged to several communist front organizations.

Over this harrowing period, Urey lost faith in the ability of modern secular society to manage the new threats of the atomic age. Although he had long abandoned his parents' religion, he began to argue that Judaeo-Christianity was key to democracy. He attributed the success of science itself, with its commitments to honesty and credit, to religious ethics.



The Life and Science of Harold C. Urey
MATTHEW SHINDELL
University of Chicago Press (2019)

In the late 1940s, Urey used his expertise in mass spectrometry to begin work in geochemistry, and then in planetary science. It was a way to escape the orbit of the nuclear weapons establishment (although he still advised the US Atomic Energy Commission). With chemistry graduate Stanley Miller, he tested hypotheses on the origins of life by Soviet biochemist Alexander Oparin and biologist J. B. S. Haldane, and successfully produced amino acids by sparking a solution of water, methane, ammonia and hydrogen. In 1952, Urey published *The Planets*, a chemical treatise on the formation of the Solar System.

LUNAR QUEST

Urey became influential during the early days of NASA, formed after the 1957 launch of the Soviet satellite Sputnik, offering the agency persuasive reasons to prioritize exploration of the Moon over other bodies. In 1969, he analysed lunar rocks collected during the Apollo 11 mission, which supported his theory of the Moon's common origin with Earth. He wanted the well-funded agency to test theories about the origins of the Solar System — experimentation beyond the reach of individual university scientists. Despite his influence, he was disappointed in this: NASA focused on crewed space exploration over questions of cosmogony. This last, frustrating chapter of Urey's life sheds light on the politics of mission-oriented research, in which popular interest or government priorities can take precedence over scientific questions.

Shindell keeps a tight focus on his biographical subject throughout the book. At times, the reader might wish that he had panned out a little more, to sketch the landscape of US cultural life in Urey's era, or comment on how the space race fitted within the global cold war. But this fine biography wonderfully shows how Urey's scientific contributions led chemistry in new directions, including to the Moon — and, in depicting the life of a leading scientist, Shindell probes the complex interplay of faith, values and politics in the United States. ■

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