COSMOLOGY'S NEEDLE IN A HAYSTACK: TUNING INTO THE FAINTEST WHISPER OF THE EARLY UNIVERSE

Jacob Tutt and Harry Bevins explore how the 21-cm signal from neutral hydrogen helps uncover the history of our universe.

The last few decades have seen the study of our universe transform from a largely theoretical frontier into a data-rich reality, marking a definitive shift into the era of 'precision cosmology'. With access to a plethora of datasets across the electromagnetic spectrum, astronomers are now able to examine various periods of cosmic history with unprecedented scrutiny ... yet a crucial chapter remains largely uncharted.

Our earliest observational record exists as a snapshot of relic radiation left over from the Big Bang, known as the Cosmic Microwave Background (CMB). This primordial blueprint from when the universe was around 380,000 years old reveals an epoch of simplicity, in which matter and radiation exhibited density fluctuations of just one part in 100,000, reflecting an extraordinary degree of uniformity. In striking contrast, modern surveys mapping the nearby cosmos paint a very different picture: a richly structured cosmic web of galaxies, filaments, and vast underdense voids.

Despite these two well-characterised bookends enabling stringent constraints to be placed on the fundamental parameters governing the Universe's evolution, much of the vast interval of cosmic history separating them remains unexplored. As a result, many fundamental questions are left unanswered. Theoretical models suggest that this period, spanning from the formation of the CMB to roughly one billion years after the Big Bang, can be divided into three distinct epochs. The earliest of these, the 'Dark Ages', saw initial gravitational instabilities slowly collapse, giving rise to the first structures. Within the hearts of these newborn haloes, the first stars ignited, marking the onset of the 'Cosmic Dawn'. Their radiation then gradually transformed the surrounding intergalactic medium, culminating in the `Epoch of Reionisation', when the Universe transitioned from a largely neutral state to the ionised, transparent cosmos we inhabit today. However, the timing of the major milestones in this transformation, and the pace at which they unfolded, remain shrouded in mystery.

While the unprecedented sensitivity and angular resolution of the James Webb Space Telescope is currently revolutionising our understanding of the closing chapters of this period, even it, and future observatories, face fundamental physical limitations. The first flickers of light from the 'Cosmic Dawn' are simply too faint — and too deeply veiled by primordial gas — to remain within reach of direct detection.

However, hope is not lost. Where traditional telescopes see an impenetrable fog, radio observatories can hear an articulate broadcast.

Astrophysicists have shown it is possible to uncover the properties of the earliest populations of stars, galaxies, and black holes not through direct observation, but by studying the imprint they left on the neutral hydrogen that once permeated space. At the most fundamental level, hydrogen's constituent proton and electron both possess a quantum property known as `spin', and their relative alignment places the atom in distinct energy states. The exceptionally subtle transition between these two states with aligned and anti-aligned electron and proton spins allows hydrogen to absorb or emit a photon at a characteristic radio frequency of 1.4 gigahertz, corresponding to a wavelength of 21 centimetres. Although vanishingly rare for any single atom, this transition, integrated over the immense volume of neutral hydrogen in the infant Universe, produces a measurable statistical signal that appears in absorption or emission against the background radiation from the Big Bang.

The strength and evolution of this signal promise a unique way to address some of the most fundamental questions remaining in astrophysics and cosmology. When did the first galaxies form? How big and bright were they? How did the light that they emitted affect the surrounding gas and formation of subsequent generations of galaxies? How quickly did exotic objects such as X-ray binary and black holes form and how abundant were they? Each of these possibilities would leave a distinct imprint on the depth, timing, and overall shape of the 21cm signal, offering a powerful way to test competing hypotheses about the origin of the first structures.

Crucially, it is cosmic expansion that makes the 21cm signal from neutral

probe. As the Universe expands, the signal is stretched to progressively longer radio wavelengths, allowing astronomers to trace its evolution and reconstruct a timeline of early structure formation. However, this very stretching also renders the signal notoriously difficult to observe, shifting it into a frequency range dominated by foreground emission (from our own galaxy and beyond) that is four to five orders of magnitude brighter.

What remains is only a faint murmur, nearly lost beneath far louder foreground emissions.

Researchers at the Cavendish Laboratory, the Institute of Astronomy, and the Kavli Institute for Cosmology are pursuing this elusive signal through two complementary approaches. The Radio Experiment for the Analysis of Cosmic Hydrogen (REACH), a collaboration between the University of Cambridge and Stellenbosch University, aims to use a highly stable radio spectrometer to detect the so-called global signal. Deployed deep within the quiet, sparsely populated plains of South Africa's Karoo Desert — where human-made radio interference is kept to an absolute minimum — REACH measures the evolution of the sky-averaged emission across cosmic time. Isolating this faint imprint from the inescapable radio foreground and interference like FM radio is, however, an extraordinary challenge. Success demands an unprecedented understanding of both the sky itself and the instrument used to observe it, driving the development of sophisticated data-analysis and machine learning techniques, alongside state-of-the-art precision radio engineering.

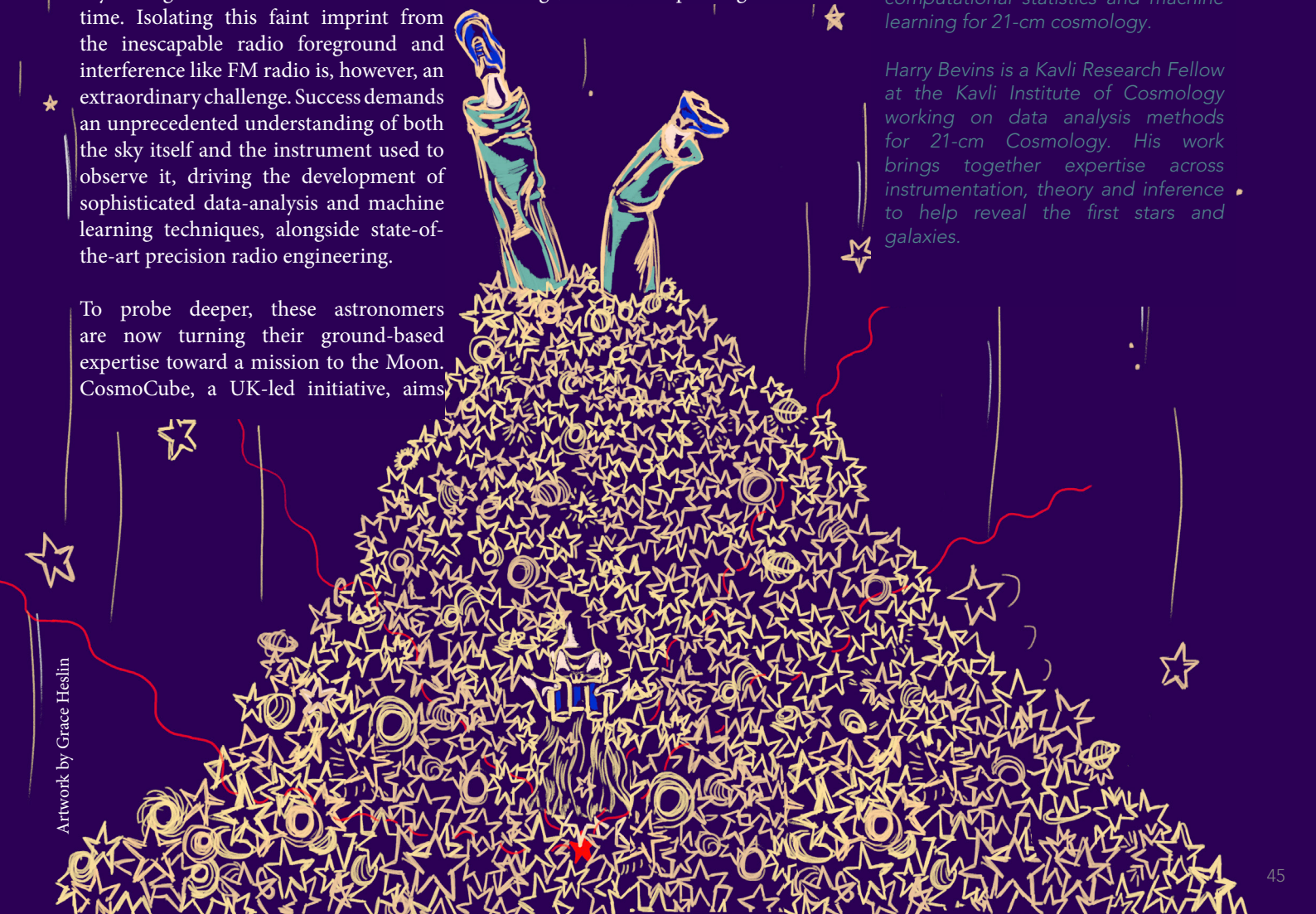
To probe deeper, these astronomers are now turning their ground-based expertise toward a mission to the Moon. CosmoCube, a UK-led initiative, aims to exploit one of the quietest radio environments accessible: the lunar far side, permanently shielded from Earth's incessant radio chatter and free from the shimmering distortions of Earth's ionosphere. From a CubeSat stationed in this uniquely silent setting, CosmoCube will listen for the faintest whispers from the Universe's earliest and most elusive chapter before even the first stars formed, revealing the nature of dark matter.

While instruments like REACH and CosmoCube look for the sky-averaged signal over time, radio cosmologists are also looking for the spatial fluctuations in the 21cm signal. Using vast networks of radio antennas, they aim to assemble a three-dimensional map of the Universe's earliest structures through tiny variations in the emission from hydrogen across the sky and through cosmic epochs. Achieving the required sensitivity has motivated the construction of the Square Kilometre Array (SKA), the largest radio telescope ever built. Spread across the remote landscapes of Western Australia, the SKA's low-frequency component alone will consist of more than 131,000 antennas operating in unison as a single observatory to detect the 21cm signal. Often dubbed the ultimate 'Big Data' challenge, the SKA is pushing the limits of modern computing, with data rates expected to exceed 150 terabytes per second – enough data to fill around 2.5 million laptops every day. At this scale, the challenge becomes as much computational as it is astronomical. Extracting a faint cosmological signal from such overwhelming data volumes is catalysing advances in high-performance computing, statistical inference, and artificial intelligence to recognise subtle patterns buried deep within noise.

While the challenges of detecting the 21cm signal are immense, success from REACH, CosmoCube, the SKA, or one of the many other instruments targeting this signal would reveal a formative chapter of cosmic history that has so far remained beyond observational reach. Such measurements promise to transform our understanding of the Universe, shedding light on its expansion, the role of dark matter, and the emergence of the first stars and galaxies.

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Artwork by Grace Heslin