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Mystery of the cosmic dawn: What's eating the first starlight?

A shoestring experiment in the Australian outback has seen the signal of the very first stars – and a weird effect astronomers are struggling to explain

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By **Colin Stuart**

IN THE dusty, dry outback of Western Australia there is nothing for miles around but red dirt, unpaved roads and the occasional kangaroo. A journey across this alien landscape is a lesson in solitude – just you and the road, a 4×4 as essential as a sense of adventure. Astronomer Judd Bowman at Arizona State University has been coming here for nearly a decade to visit the Murchison Radio-astronomy Observatory, an old sheep and cattle station repurposed as a place to listen to the universe.

It hardly seems the stage for a scientific revolution, meagre compared with the cathedral-like majesty of machines like the Large Hadron Collider at CERN. Yet what Bowman and his colleagues have discovered here, using a telescope half the size of a ping-pong table, spells trouble for our picture of the early universe.

It could mean that our ideas about dark matter, the mysterious glue that holds the universe together, are all wrong. It could be that gravity, the force that determines how the cosmos evolves, doesn't work how we think it does. Or maybe black holes were eating into the early universe long before we thought possible. One thing is certain: if Bowman's results hold up – and it's a big if – this could be a milestone moment in the history of cosmology.

When Bowman first started jeeping across the outback in 2009, he was chasing the bright lights of the early universe. In the aftermath of the big bang, the cosmos was full of hydrogen atoms, floating alone in the frigid darkness. As millions of years sailed by, clouds of hydrogen gas started to clump together in ever denser clusters. When their density hit a critical point, the energy of nuclear fusion caused them to emit light – signalling the birth of the first stars in a moment known as the cosmic dawn.

For the past 20 years, astronomers have been on the hunt for a signal from this moment: the turning point when the lights switched on in a dark, infant universe. As the intense light from the first stars excited the surrounding hydrogen gas, it primed it to absorb some of the cosmic microwave background – the leftover energy from the big bang – at a very specific frequency. This would be an unmistakable signal of the dramatic epoch of reionisation.

"Some are predicting it could be worth two Nobel prizes"

In the race to detect this, Bowman's experiment was far from being the front runner. Most astronomers had plumped for big arrays consisting of multiple radio dishes strung together. The Hydrogen Epoch of Reionization Array experiment in South Africa, for example, is a hexagonal grid of dishes covering an area 300 metres wide. Bowman, a David to some pretty impressive Goliaths, relied instead on a single table-sized detector with just one antenna.

Taking the road less travelled appears to have paid dividends. In February 2018, Bowman was first to announce the detection of just such an absorption signal using the Experiment to Detect the Global EoR Signature (EDGES) at Murchison. While neutral hydrogen ordinarily absorbs radiation with a wavelength of 21 centimetres, the universe's expansion over billions of years stretched this signal out to 385 cm. Bowman calculates that means the first stars ignited just 180 million years after the big bang, earlier than most astronomers were expecting.

That discovery in itself was enough to send tremors through the world of cosmology. Yet that's only half the story. Although Bowman found the kind of signal everyone was looking for, the absorption was far larger than anything anyone had expected.

With the stakes so high, Bowman was cautious from the outset. Within weeks of switching on the EDGES antenna at Murchison, he knew things were odd. "We assumed something was wrong with the instrument," he says. Bowman and his colleagues spent two years meticulously checking everything from loose screws to competing signals. Rotating the antenna didn't change anything either. The absorption signal persisted. "Our confidence started to grow," he says. By last summer, he was treating it as a bona fide detection and began sharing his find with a select few colleagues he hoped could help resolve the mystery. One of those he emailed was Rennan Barkana, a dark matter specialist from Tel Aviv University in Israel. "He told me he had found something weird and wondered whether I had any explanation for it," says Barkana.

The EDGES detector ended a 20-year quest to spot the first stars switching on
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Barkana mulled it over during a long car journey with his family. He came to the conclusion that the extra absorption was because the hydrogen gas surrounding the first stars was cooler than had been predicted, allowing it to absorb more of the cosmic microwave background radiation. Barkana decided there was only one thing around to cool the gas: dark matter.

Dark matter was put forward to fill a strange role in the universe. Invisible, it makes up the vast majority of all the matter out there, leaving all the stuff we can see – stars, sheep, cattle and 4x4s included – to fill up a paltry 16 per cent. Regular matter is easy enough to hunt for. But dark matter, defined by its very obscurity, is almost impossible to spot. Up until now, the only signs of its existence have been gravitational: slimline galaxies that rolled ponderously around their axes as though carrying invisible bulk. What Bowman has spotted may turn out to be the first independent sign the shadowy stuff is out there. If so, it may prove such a game-changing discovery that it makes our existing dark matter searches obsolete. All this from an experiment only a few metres across in the middle of nowhere.

On the face of it, Barkana's hypothesis of gas-cooling dark matter isn't too much of a stretch. After all, dark matter has been in the universe since its inception. It first crossed our radar in the 1930s, when astronomers found galaxies and galaxy clusters moving faster than we would expect given the mass of their visible matter alone. Since then, similar clues have come from experiments looking at how light is bent by massive clusters of galaxies. Astronomers observe too much bending given the amount of material we can see in the cluster. However, these are all indirect lines of evidence that involve gravity, causing a growing band of theorists to suggest that gravity itself might vary across the universe, with dark matter being no more than a figment of our imagination.

Bowman's result could change all that. "It's the first direct evidence of dark matter that doesn't rely on gravity," says Barkana. But it's not the dark matter most people expected.

In the late 1980s, astronomers trying to work out what dark matter might be made of turned to particle physicists for help. Based on the available data, they suggested it could take the form of heavy particles that interacted with other matter too weakly to be observed directly. These weakly interacting massive particles (WIMPs) rapidly became our top dark matter candidate, and in recent years researchers have gone to great lengths to snare one. Experiments have been set up under the Antarctic ice, deep underground in abandoned mines, and strapped to the International Space Station. Atom smashers like the Large Hadron Collider have been searching too. "There's been a very large investment in searching for WIMPs, but they haven't found anything," says Barkana. "It's been getting more and more frustrating."

If dark matter were responsible for the unusually strong signal of the cosmic dawn, then Barkana believes it can't be made of WIMPs. In order to interact with regular matter strongly enough to funnel away heat, it would have to be formed of much lighter particles, and possess a tiny electric charge.

"It may turn out to be the first direct sign that shadowy dark matter is out there"

Avi Loeb, an astrophysicist at Harvard University, is both elated and cautious. On the one hand, he thinks two Nobel prizes might be on offer: "one for the detection and one for the new physics." That said, he adds, "extraordinary claims require extraordinary evidence". He points out that the signal Bowman was looking for is incredibly faint. Our Milky Way galaxy produces similar signals 10,000 times stronger than the ones EDGES was trying to pick up. Bowman had to model those foreground signals and remove them to see what was left. "I'm worried that this procedure has introduced an artificial absorption signal," Loeb says.

Bowman freely admits the result needs further scrutiny. "We want another team with another instrument to confirm this signal, particularly as what we're seeing isn't what people expected," he says, "but we're excited to see a signal people have waited 20 years for."

Even if the signal turns out to be genuine, it might be too early to mourn the demise of the WIMP. Dan Hooper, an astrophysicist at the University of Chicago, argues that if dark matter is completely made of particles lighter than WIMPs then they would also have interacted with normal matter at the time the cosmic microwave background was released and we would see evidence of that. "It would have screwed up the cosmic microwave background quite severely," he says. Instead, these new particles have to make up somewhere between one-third of a per cent and 2 per cent of the total composition of dark matter. That's not much wiggle room.

What's more, Sam McDermott from the Fermi National Accelerator Laboratory near Batavia, Illinois, takes issue with Barkana's hypothesised electric charge. He says astronomical observations limit the charge on any light dark matter particle to around one hundred thousandth that of the electron. So not only would ordinary dark matter need to be peppered with just the right amount of lighter dark matter particles, we would also need them to have just the right electric charge. "It's possible, and we can construct models like that, but it's not something that is easy to orchestrate," Hooper says. He sees that as a reason to be sceptical of a dark matter interpretation of the signal. "It's not a particularly good bet."

Defying gravity

To Stacy McGaugh, an astronomer at Case Western Reserve University in Ohio, it is no surprise that these explanations for the excess absorption run into trouble. He doesn't think dark matter has anything to do with it. "It is very natural without dark matter," he says. McGaugh has been working for two decades on alternatives to dark matter, in particular the idea that the laws of gravity are not the same across the entire universe. Such theories of "modified gravity" have been gaining traction in recent years in response to our inability to find concrete evidence of WIMPs. "With dark matter you expect the universe to expand slowly," McGaugh says, because its gravity applied the brakes. Without dark matter the universe expands more quickly, creating more space between the cosmic microwave background and the first stars. That means more gas between the two and therefore a greater amount of absorption than had been anticipated. "If the signal is real then it's more consistent with this picture than dark matter," he says.

There is another way to explain the enhanced absorption signal without the need to dispense with WIMPs or to invoke modified gravity. "The assumption is that it's only the cosmic microwave background being absorbed," says Gil Holder, a theoretical astrophysicist at the University of Illinois. "But if there were additional radio waves kicking around at that time then those would also be absorbed by the cold gas and that would enhance the signal." And there is a hint that might be the case.

Almost a decade ago, the ARCADE 2 experiment found an excess of radio waves in a survey of the sky. Even today that excess has no accepted explanation. According to Holder, if only 1 or 2 per cent of that excess was around when the first stars lit up that could explain the strength of the signal picked up by EDGES. However, he says, it would require some new astrophysics to explain where the extra radio waves came from. One possibility is primordial black holes, roaming the universe long before the standard theory of cosmology predicts. "So the only question is whether that's more or less plausible than dark matter interacting with strange properties," he says. "I think that's a personal choice between how weird astrophysics can be compared to how weird particle physics can be."

First things first, the strength of this absorption signal is so unexpected that physicists are still playing catch up to try to establish whether it is genuine. That revelation could come by December. Should a discovery be confirmed, only then will attention turn to working out whether dark matter really is responsible – and for that we need a much bigger collection of radio dishes to create a 3D image of the hydrogen gas. "If the origin of the cooling has to do with dark matter you would get a very different 3D map compared with if it's associated with extra radio waves," says Avi Loeb. As it happens, our best bet is the Square Kilometre Array, currently under construction in South Africa and Australia, on the same remote site as Bowman's own tabletop experiment. It seems this may not be the last time our picture of the universe is shaken up from the dusty outback.

The 21-centimetre stretch

Astronomers search for the light of the first stars by looking for its effect on neutral hydrogen. When excited, hydrogen atoms absorb light at a distinctive 21-centimetre wavelength. As the universe expands, these waves expand with it, allowing us to tell how much time has passed since the hydrogen was excited.

Judd Bowman from Arizona State University has picked up a surprisingly strong signal at a wavelength of 385 centimetres. If the signal corresponds to the stretched 21-centimetre radiation, it seems to indicate that hydrogen was absorbing light from the first stars just 180 million years after the big bang, 220 million years earlier than thought.

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