Interstellar space: The mysterious realm beyond our heliosphere

Interstellar space may seem like unbroken nothingness, but thanks partly to the Voyager probes, we're getting many new insights into this region's exotic chemistry, strange waves and vast bubbles

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The jokes came easily for Thomas Bania when he began studying the properties of the empty space beyond our solar system. "I remember the look on my father's face when I was in graduate school," he says. "I told him I was an expert in nothing."

Most of us can see why Bania's dad hesitated over his son's choice of specialism. The exciting bits of the universe are the shining stars, the exotic planets, the icy comets. Isn't interstellar space just a featureless void – and so far away as to be tough to study anyway?

Not so. All the atoms in the universe's stars and planets account for only a piffling 4 per cent of its regular matter. The rest is spread out thinly in the gaps between the stars, in interstellar and intergalactic space. By that measure, what we normally think of as measure, what we normally think of as "empty space" isn't nothing – it is almost everything.

Over the past decade or so, researchers like Bania have been showing that interstellar space is deeply fascinating. This so-called nothingness is brimming with exotic molecules, pulsating with radio waves and divided into gigantic bubbles, each with their own character. Now, as we are beginning to map out our place within the void more keenly, we are coming to see that this variety matters immensely – and that as the solar system heads towards a new region of interstellar space, there could be important ramifications for life on Earth.

We are used to living in a thick soup of atmosphere. In a cubic centimetre of air, a volume the size of a six-sided dice, there are trillions of atoms. Gas, dust, water vapour, viruses, pollen and more all waft around. Just beyond our atmosphere, however, in interplanetary space, the conditions are close to a perfect vacuum. "Space is huge, and it's mostly empty," says Seth Redfield at Wesleyan University in Connecticut. Out there, the same volume contains, on average, just five atoms.

This matter mostly consists of charged particles streaming out from the sun as the particles streaming out from the sun as the solar wind. We have known for decades about this flow of material and how it creates a protective zone around the solar system called the heliosphere. It cocoons us from high-energy cosmic rays shooting at us from deep space – and a good thing too, because those rays can damage the cells and DNA in living things. Radiation levels are eight to 10 times higher outside this zone. "Without our heliosphere, would life even exist?" asks Jamie Rankin at Princeton University. Much about this crucial zone remained a mystery for a long time, though, not least where it ends and where interstellar space begins.

The Voyager probes

That changed thanks to two space probes, Voyager 1 and 2. They both launched in 1977 and were sent on different trajectories, with the principal aim of exploring the outer planets of the solar system. But once they had flown past them, they kept on going towards the inky blackness of interstellar space.

In 2012, Voyager 1 recorded a huge drop in the strength of the solar wind and a simultaneous rise in the number of incoming cosmic rays. This occurred at 122 astronomical units (AU) from the sun (one AU is the distance between Earth and the AU is the distance between Earth and the sun, about 150 million kilometres). This, scientists later declared, was the heliopause, the edge of the heliosphere. Voyager 2 had taken a longer route heading out at a slightly different angle to its twin, but, in 2018, it also detected the heliopause at a similar distance from the sun.

At the heliopause, the interaction of the outflowing solar wind and the incoming interstellar medium results in temperatures of tens of thousands of degrees Celsius, causing particles to move at high velocity. But the sparseness of matter here – barely a single atom per cubic centimetre in the interstellar medium – means you would still freeze to death.

That is because in order to heat anything up, particles would have to collide with it, and with so few particles, that would take an awfully long time. The density of matter out here is equivalent to “an orange inside the volume of Earth”, says Bania. “The very best laboratory vacuums we can produce are a million times denser.”

There are still many mysteries about the heliopause, though. For instance, when researchers analysed data sent from Voyager 2 in 2019, they found it appeared to have a smoother passage through a thinner section of heliopause than Voyager 1. We don’t know why.

The shape of the heliosphere

Then there is the more fundamental question of the shape of the heliopause. Our solar system is moving through the surrounding interstellar medium, which pushes against the heliosphere and distorts it. For this reason, the leading nose of our heliosphere is widely agreed to be rounded. But the shape of its “tail” remains controversial. Many favour a simple teardrop form.

However, astronomer Merav Opher at Boston University in Massachusetts and her colleagues have been working on a NASA funded project called Shield, using data from observations of the heliosphere to build computer models of it. This work led Opher to argue in 2021 that the heliosphere is shaped like a croissant, with a two-pronged tail. With more probes designed to observe the heliosphere set to launch in the coming years, Opher reckons the question could finally be settled.

As well as finding out where interstellar space starts, we are discovering more and more about what it contains. We know there is a scattering of atoms and dust and that the density of this medium can vary considerably throughout our galaxy. “If interstellar space were uniform and smooth, it’d be much less interesting,” says Bruce Draine at Princeton University. It was always thought, however, that complex molecules couldn’t exist in interstellar space, as they would surely be ripped apart by the barrage of powerful cosmic rays.

But in 1970, astronomers Robert Wilson and Arno Penzias – famed for their accidental discovery of the cosmic microwave background radiation, the afterglow of the big bang – saw a signature of carbon monoxide in the Orion nebula, a gas-rich region of our in the Orion nebula, a gas-rich region of our galaxy.

The discovery kick-started a new field, the study of molecules drifting in the interstellar medium. Bania is one of those who led the charge. “The big breakthrough in my lifetime was the whole discovery of molecules in interstellar space,” he says. As of 2022, some 256 types had been found, mostly identified from the way they absorb specific wavelengths of passing radio waves. “We found this rich molecular chemistry in space,” says Bania.

Some of these molecules are complex hydrocarbons. Even simple amino acids, the building blocks of proteins, have been spotted. That led astronomers to explore whether the ingredients of life could have been delivered to planets like Earth across interstellar space, either floating freely or on comets or asteroids, something that remains unanswered today. “It’s a very interesting question,” says Alexander Tielens at Leiden University in the Netherlands. “Did life start somewhere in the universe and spread? Or do we just have conditions everywhere that are amenable to the formation of life?”

Just as interstellar space isn’t empty, it isn’t a still, tranquil zone either. Instead, it is like an ocean full of waves. We learned this, again, from the Voyager probes. In 2021, when Stella Koch Ocker at Cornell University in New York and her colleagues analysed data sent by Voyager 1 from beyond the heliopause, they were surprised to find waves of radio activity washing over the spacecraft. These were caused by events from the sun seeping through the heliopause and interacting with the interstellar medium. “It’s really exciting,” says Rankin.

Interstellar space may have waves like an ocean, but it isn’t an unbroken expanse. Instead, it is divided into many bubbles, each with its own character. This was originally recognised in 1992 by astronomer Rosine Lallement at the Paris Sciences et Lettres University in France.

Local Interstellar Cloud

By studying the motion of sodium gas in our corner of the galaxy, she found that the solar system was moving through a cloud of dust and gas about 10 light years across, now known as the Local Interstellar Cloud. She also realised we were heading out of that bubble and towards another one called the G-cloud (see “A new bubble”, above). “It was a big moment in my career,” says Lallement. Within a year, detections of the flow of interstellar helium gas by NASA’s Ulysses spacecraft would support the findings.

Later work by Lallement and others using the Hubble Space Telescope has helped pinpoint our position more accurately by measuring the motion of our sun with respect to our neighbouring star system Alpha Centauri. This showed that our solar system entered the Local Interstellar Cloud about 60,000 years ago and will pass into the G-cloud in about 2000 years. In cosmic terms, we are right on the edge.

What happens when we enter this new bubble? The good news is that the G-cloud appears to have a similar density to our Local Interstellar Cloud, meaning few changes. The bad news is that the character of the boundary between the clouds is of the boundary between the clouds is uncertain. It isn’t clear if they are touching or if there is an intermediary region of different density between.

If we encounter a higher density region, that could push more heavily on our heliosphere, causing it to shrink and allowing harmful cosmic rays to penetrate deeper in towards the solar system’s rocky planets like Earth. That would be unwelcome.

A higher flux of cosmic rays might increase Earth’s cloud cover and cool our climate, and it could also cause more genetic mutations in cells as high-energy particles enter our bodies. “Earth would see the effects [of cosmic rays] much more than at present,” says Jeffrey Linsky at the University of Boulder, Colorado. On the other hand, if we enter a region of lower density, the heliosphere could expand, increasing the volume of space that is shielded from cosmic rays and possibly boosting the habitability of areas at the distant edges of the solar system.

On a grander scale, our 10-light-year-wide Local Interstellar Cloud resides in a much larger, irregularly shaped structure called the Local Bubble, which is 1000 light years across. This is a giant shell of expanding gas formed by more than a dozen stars exploding formed by more than a dozen stars exploding as supernovae, with a density around a tenth that of the space outside the Local Bubble. Recent estimates have suggested that our solar system entered this bubble about 5 million years ago, and we are now roughly at its centre.

In another 8 million years, it is predicted we will reach its edge. In 2022, Catherine Zucker at the Space Telescope Science Institute in Maryland and her colleagues used the European Space Agency's Gaia telescope to track the motions and positions of stars in our vicinity. This showed that the centre of the Local Bubble is relatively empty, but that the edges have a much higher density of material. "We're accidentally in a great position," says Zucker.

Yet that could change as we near the edge. Ongoing work by Opher suggests the higher Ongoing work by Opher suggests the higher pressure we would experience as we near the edge of the Local Bubble would shrink the heliopause to the wrong side of Earth's orbit, exposing us to far more cosmic rays. Earth would be "in interstellar space", says Opher. It is reasonably well known that the sun will get much hotter over the next billion years, hot enough to boil Earth's oceans away. But our traverse of interstellar space could have its own serious consequences for life on Earth far sooner. "Where we were in the past and where we are going to be in the future is critical," says Opher. "I think it will have a direct effect on habitability."

We can only learn so much about interstellar space while studying it from within our solar system. That is why scientists are now proposing new missions that would surpass the work of the Voyager craft and be equipped with instruments specifically designed to study the great beyond.

Missions to interstellar space

In the US, a proposal called Interstellar Probe is being considered by NASA, with a decision as to whether it gets funding expected by the end of 2024. This 50-year mission would launch in the 2030s and reach the heliopause in 15 years, before travelling perhaps 10 times further than the Voyager perhaps 10 times further than the Voyager craft have. "The whole idea is to get far beyond the heliopause into the pristine interstellar medium," says Linsky, who is part of the mission's science team.

One of the key goals would be to take an image of our heliosphere – you might call it the ultimate selfie – and so deduce its shape once and for all. This would be done using an instrument designed to detect atoms from our sun hitting the interstellar medium, revealing whether it is a croissant shape like Opher expects or something else.

Another proposed mission, from China, called Interstellar Express and comprising two craft intended to launch later this decade, would carry similar instruments, providing views from different positions outside the solar system, giving us a better understanding of the heliosphere's shape. These missions could also directly study remnants of the supernovae that fashioned our Local Bubble, perhaps telling us when and where some of these explosions took place. "We're beginning to piece that together," says Jesse Miller at the University of Illinois Urbana-Champaign.

The interstellar medium is much more than just the gap between the stars. It is the ocean in which our sun and all the other ocean in which our sun and all the other stars in our galaxy sail. More than ever, we know where we are in this ocean. "It's kind of extraordinary," says Rankin. "We're starting to look back on ourselves from the outside now for the first time."