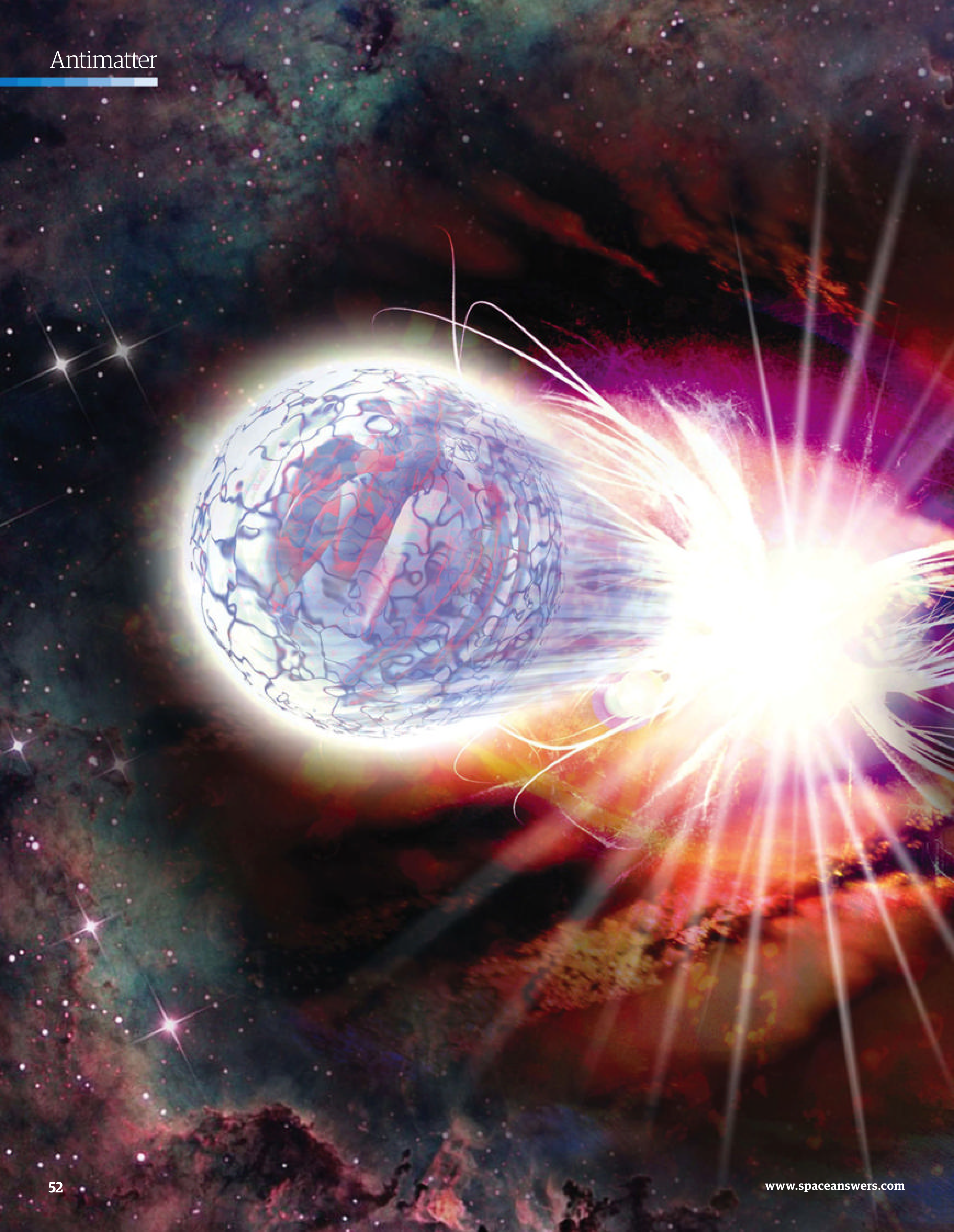
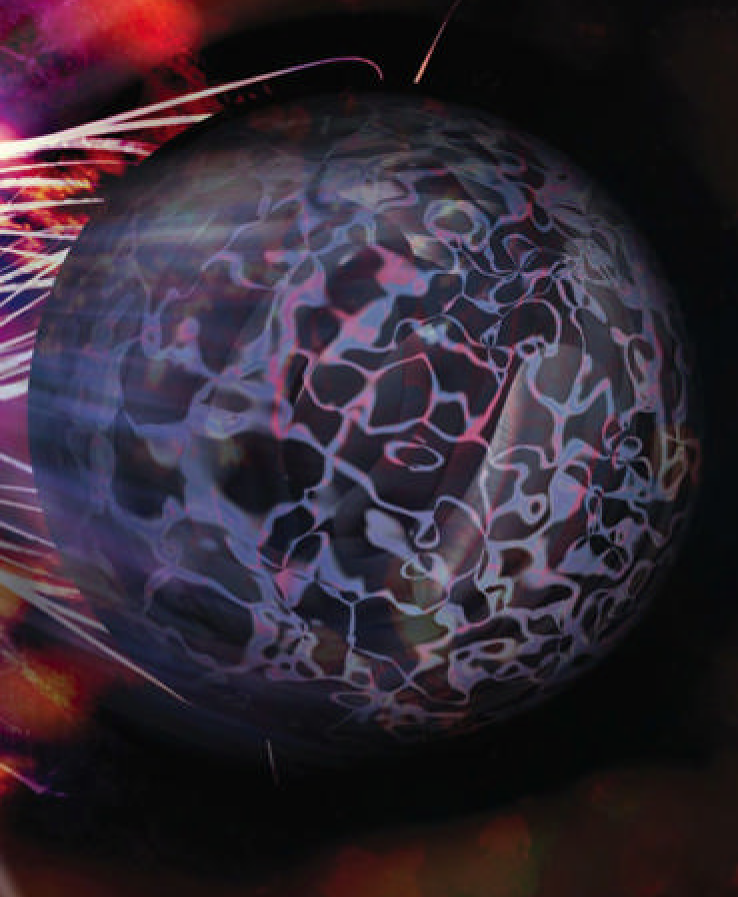


THE POWER OF ANTIMATTER

Is antimatter the key to understanding more about our universe and propelling future spacecraft between the stars? **All About Space** investigates how close we are to finding out more about this exotic matter

Written by Gemma Lavender



Imagine a mirror held up to the universe, one that reflects matter on the scale of particles. Just like a normal mirror, the image would be reversed. Particles like protons with positive charge would suddenly look to be negatively charged, while electrons that spin in quantum fashion one way would appear to spin the other way. While the universe doesn't really have a mirror, particles of matter do have mirror images of themselves, known as antimatter.

"[Matter and antimatter] are equal and opposite, that's the theory so far," says antimatter researcher and spokesperson for CERN's Antihydrogen Laser Physics Apparatus (ALPHA), Jeffrey Hangst. "The antiparticle equivalent - antiprotons, antineutrons and positrons - are just like their matter counterparts but they have an opposite charge in the case of the charged particles and when they meet they annihilate."

So when the two clash, they do so explosively. Just as Einstein's famous equation $E=mc^2$ describes the equivalence of mass and energy, when a particle and an antiparticle come into contact with each other, they utterly annihilate in a flash - there one moment, gone the next - converting all their mass directly into energy. It's for this reason that, if antimatter could be harnessed, we would have an impressive energy source on our hands. The trouble is, there's just not that much antimatter about.

That's the major problem with antimatter, especially when its far more common counterpart - common matter - is found lurking everywhere. Antimatter can be created then destroyed in such a short space of time that experts do not have much time to hold antimatter down long enough for us to question what about its existence makes it special. As a result, there are not only gaps in our knowledge when it comes to this shy matter itself, but also in our theories of how the cosmos came into existence. "The names matter and antimatter are a bit arbitrary," adds Hangst. "We believe that if you built a universe out of antimatter it would behave in the same way, so we don't know why nature chose one over the other."

Without a doubt, the Big Bang is a widely supported theory and it tells us that matter and antimatter should have been created equally at the beginning of time around 13.8 billion years ago. They should have annihilated each other leaving nothing behind, but we exist today in a universe with plentiful matter and scarcely a drop of antimatter. Thanks to our natural curiosity for exploring things and taking things apart to reveal the fundamental building blocks of matter, one thing remains unclear; what happened to the antimatter that once existed?

"[The study of antimatter] is motivated by the fact that we believe that matter and antimatter should have been produced in equal quantities at the [time of the] Big Bang and as far as we can observe so far the universe just contains matter, so we don't really know what happened," explains Hangst. "None of the theories that we have, or the so-called standard model [of particle physics] tell us what happened to the antimatter. That's one of the biggest unsolved questions in physics – why is there a universe at all?"

While the Big Bang is an extraordinarily successful theory, as it currently stands, we shouldn't exist since the matter from which we are built from should have been annihilated away. The University of California's Professor Joel Fajans, who has recently enlisted the help of the ALPHA experiment to investigate if antimatter and matter are affected differently by gravity, echoes Hangst's and other scientists' thoughts that maybe there has been an error in our understanding of how much matter and antimatter was produced when the universe began. "I wish I knew why the amounts produced are not equal," he tells **All About Space**. "Understanding antimatter is important to our very existence."

And so, that's what experts have been trying to do ever since antimatter was first proposed by physicist Paul Dirac in 1931; study the ying to matter's yang in the hope of locking down something substantial, providing the answers to the mysteries of space that have eluded us for so long. A year after Dirac's proposition the first antiparticle – the positron – was discovered, followed by the antiproton and antineutron two decades later.

But in our attempts to delve into ways of pinning down antimatter, scientists have hit a few snags. Creating it artificially is one thing, but making enough of it and keeping it within our grasp for long enough is quite another. "First you have to produce [antimatter], it can't exist naturally [in significant quantities] in a matter universe so there are lots of very difficult technologies that you have to master to produce it and then to hold on to it," explains Hangst. "It needs to be held in a vacuum, a very, very good vacuum."

While the likes of Hangst and other scientists all over the world have been trying to get this down to a tee, Hangst insists that we still have much to figure out. "We are still learning how to efficiently produce it and handle it in a matter universe and even if you master these techniques, you are typically dealing with small quantities. It is not like you can buy a bottle of antihydrogen and make it [many] atoms at a time, so even after all that technology you are still left with very little of the substance."

CERN has been able to produce thousands of atoms of the simplest antiatom, antihydrogen, at a time, yet capturing it has proven to be problematic. "We've only managed to trap one atom at a time," explains Hangst. "We are really talking about a very, very rare substance." Nevertheless, ALPHA has been able to trap some antiatoms for as long as 1,000 seconds – holding them still long enough for scientists to study them before they annihilate.

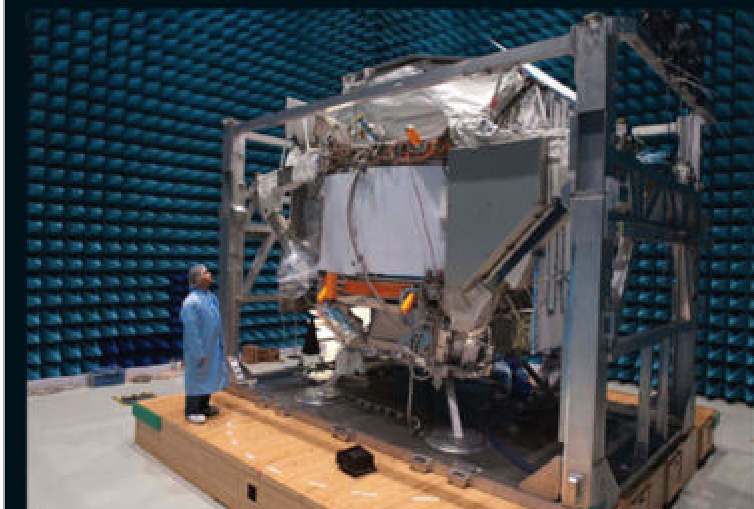
As a result of the painstaking methods used to make antiatoms, antimatter is deemed to be the most expensive material to produce with NASA suggesting that it would cost around $62.5 trillion (£41 trillion) to produce just one gram of antihydrogen. To date, only a few tens of nanograms have been created at particle accelerators like the Large Hadron Collider at CERN.

That's why as things stand antimatter is never going to be a power source of the future; there's just not enough of it to do anything with. "It takes more energy to make it than

"We are still learning how to efficiently produce it and handle it in a matter universe"
Jeffrey Hangst, CERN

Hunting antimatter

Mounted on the International Space Station, the Alpha Magnetic Spectrometer (AMS), or AMS-02, studies cosmic rays – beams of high-energy particles that permeate space – before they have a chance to interact with the Earth's atmosphere. Cosmic rays, which are believed to originate from beyond the confines of the Solar System, carry an excess of antimatter that has been detected by this sensitive particle physics experiment. This unusual excess in antimatter, or positrons, could help us to find evidence for the elusive dark matter – one of space's biggest mysteries – that is believed to account for a huge chunk of the universe's mass.



Here the AMS-02 is inside the Maxwell electromagnetic radiation chamber at the European Space Research and Technology Centre (ESTEC) for electromagnetic capability and interference testing prior to launch

Reaching a sensitivity that allows the instrument to test a greater volume of the universe than its predecessor for primordial antimatter, the AMS will study the composition of cosmic rays with a high accuracy for a decade from the ISS

A history of hunting for antimatter

1931

Existence of antimatter predicted
Theoretical physicist Paul Dirac pointed out that the Schrödinger wave equation for electrons, when considered in its relativistic form, suggested the existence of antielectrons.

1932
Scientists discover positron
During his investigation of cosmic rays, Carl Anderson from the California Institute of Technology came across unexpected particle tracks in his cloud chamber that seemed to have the same mass as the electron but an opposite, positive charge; the positron.

1955
The discovery of the antiproton
Confirmed at the University of California, Berkeley, Emilio Segrè and Owen Chamberlain were awarded the 1959 Nobel Prize in Physics for their discovery of the antiproton.

1956
Scientists discover the antineutron
Discovered at the Lawrence Berkeley National Laboratory, the antineutron was uncovered by physicist Bruce Cork in a proton-proton collision experiment.

Inside the AMS

Silicon Tracker
Hunting for matter and antimatter, this tracker is able to separate the two by determining the charge of the particle entering the AMS by measuring the deflection of the matter and antimatter.

Transition Radiation Detector (TRD)
Identifying electrons (matter) and positrons (antimatter) through the detection of X-rays thrown out by light particles, the TRD is one of the few detectors that can tell the difference between particles at high energies.

Electronics
Signals detected by the AMS's many particle detectors are converted into digital by the electronics which are analysed by computers.

The Anti-Coincidence Counter (ACC)
Spitting out a good eight out of ten particles that pass through it, the ACC, in the vacuum case, only holds on to particles that it deems useful for physics analysis.

Time-of-Flight System (ToF)
Acting as a stopwatch for the AMS, the ToF is able to measure the time it takes for a particle to pass through. The velocity of the particle can be measured up to an accuracy of 98% the speed of light. It also warns the sub-detectors of incoming cosmic rays.

Ring-Imaging CHerenkov Detector (RICH)
The velocity of a charged particle is determined from the Cherenkov effect – radiation which can travel faster than the speed of light in a particular material that produces a blue cone of light which is detected by RICH.

Magnet
At the heart of the AMS experiment rests the magnet which is able to separate matter from antimatter. It does this by bending the matter particles in an opposite direction to the antimatter particles thanks to their opposite charges.

1965
Antideuteron created in laboratory
The antiparticle of a nucleus of deuterium, antideuteron, was originally created at the Proton Synchrotron at CERN as well as at the Alternating Gradient Synchrotron at Brookhaven National Laboratory.

1995

CERN scientists observe antihydrogen
Antihydrogen was made artificially in accelerator experiments. However, the subsequent annihilation with matter meant that it could not be examined in detail.

2010
Atoms of antihydrogen trapped at CERN
The Antihydrogen Laser Physics Apparatus (ALPHA) team at CERN produced and managed to confine cold antihydrogen for about a sixth of a second, marking the technique that would see antihydrogen maintained for over 15 minutes.

2013
Scientists study antigravity for first time
Scientists uncovered the first direct evidence of how antimatter interacts with gravity. However, while it is undecided if antigravity truly exists, measuring antimatter gravity is proven to be possible.

Why is antimatter important?

1 To understand our existence
"The Big Bang should have produced as much antimatter as matter and then it should have all mutually annihilated, leaving nothing," says Professor Joel Fajans. "Yet we are here, and we've observed almost no antimatter. It's the biggest outstanding problem in our understanding of the early universe."

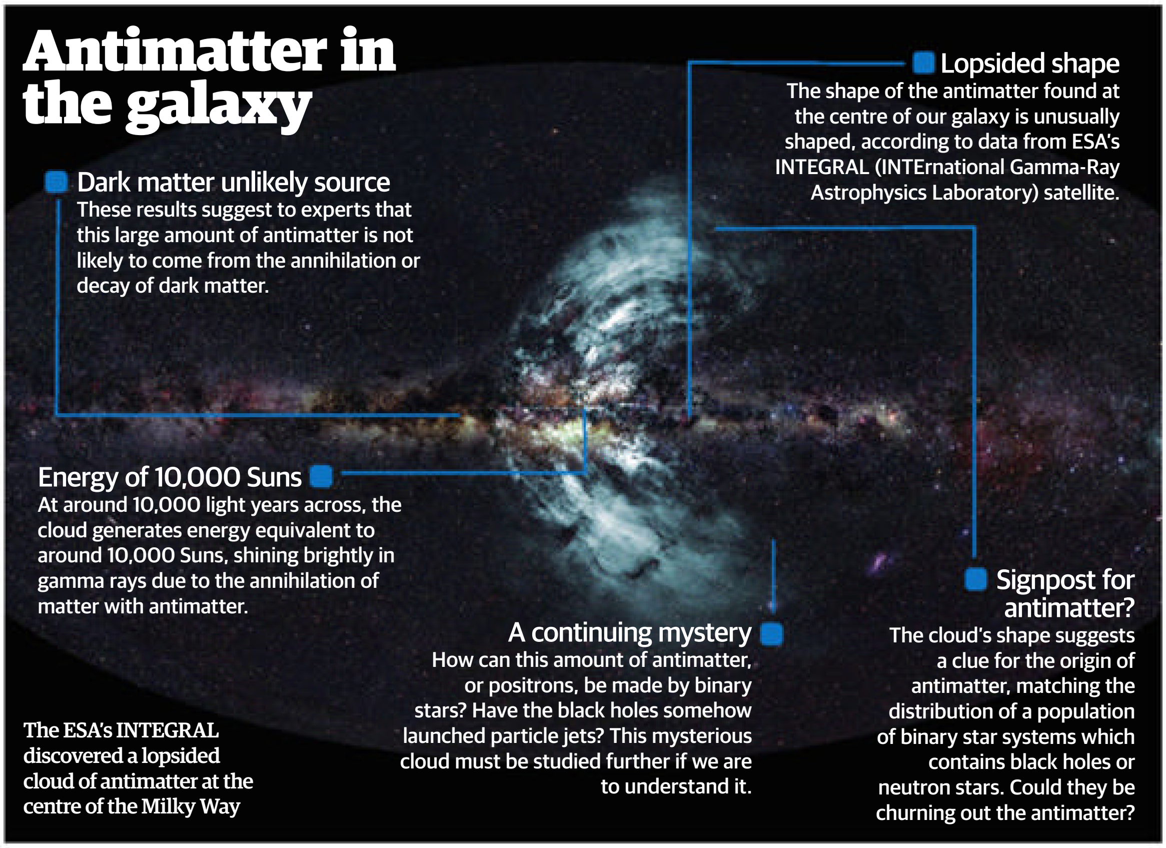
2 It could be used as fuel
Spacecraft might one day be powered by the annihilation of matter with antimatter. NASA believes that the amount of antimatter required to supply power for an engine for a one-year trip to Mars could be a millionth of a gram, providing huge thrust while being a very efficient form of propulsion.

3 For medical purposes
"Practical applications of antimatter are mostly in Positron Emission Tomography, which is revolutionising many medical fields," says Fajans. With physicians using beams of electrons, protons, neutrons or photons as well as chemotherapy, could a beam of antimatter eliminate cancer cells?

4 Possible interstellar travel
Using antimatter to voyage between the stars is currently not possible. "Making macroscopic quantities of antimatter would require all of the Earth's energy production for thousands of years," says Fajans. However, if we could create enough antimatter, we could propel starships through the cosmos.

5 Using antimatter to probe dark matter
Cosmic rays emanating from the outer reaches of the universe carry an excess of antimatter thought to be directly related to the extremely elusive dark matter. It is believed that the high amount of positrons is a result of when two particles of dark matter collide and annihilate.

Antimatter in the galaxy



The ESA's INTEGRAL discovered a lopsided cloud of antimatter at the centre of the Milky Way

you would get back, so that's a loser – that's not what you want from an energy source," states Hangst. "If some antimatter flew by and you could get a hold of it, that would be an energy source, but as far as producing it on Earth, that's just not even close."

Sadly, that means we may have to forget about antimatter-powered starships, for the moment at least. However, particle accelerators are not the only places where we can find antimatter. In 2011, 160 nanograms of antiprotons were discovered trapped in the Van Allen radiation belts above Earth, with similar amounts expected to exist in the magnetically organised radiation belts of other planets, including up to 260 nanograms around Saturn. Yet this is still a very tiny amount – add it all up and it still doesn't even come to a gram.

In the same year, astronomers announced that the Fermi Space Telescope, which observes the universe in gamma rays, had detected antimatter not coming from space, but streaming into space from above thunderstorms in Earth's atmosphere. Fermi detected high-energy gamma rays at just the right energy to indicate they were created when an antimatter particle annihilated a matter particle.

"Thunderstorm electric fields accelerate electrons to high energies," explains Professor Joseph Dwyer of the Florida Institute of Technology. "These electrons make gamma rays, which then pair-produce electrons and positrons, which are the antimatter version of the electron. The positrons may play an important role in the electrical properties of thunderstorms – it has been quite surprising how common positron production is in our atmosphere and how the positrons can actually be important for understanding thunderstorms and lightning."

> "Understanding antimatter is important to our very existence" **Joel Fajans, University of California**

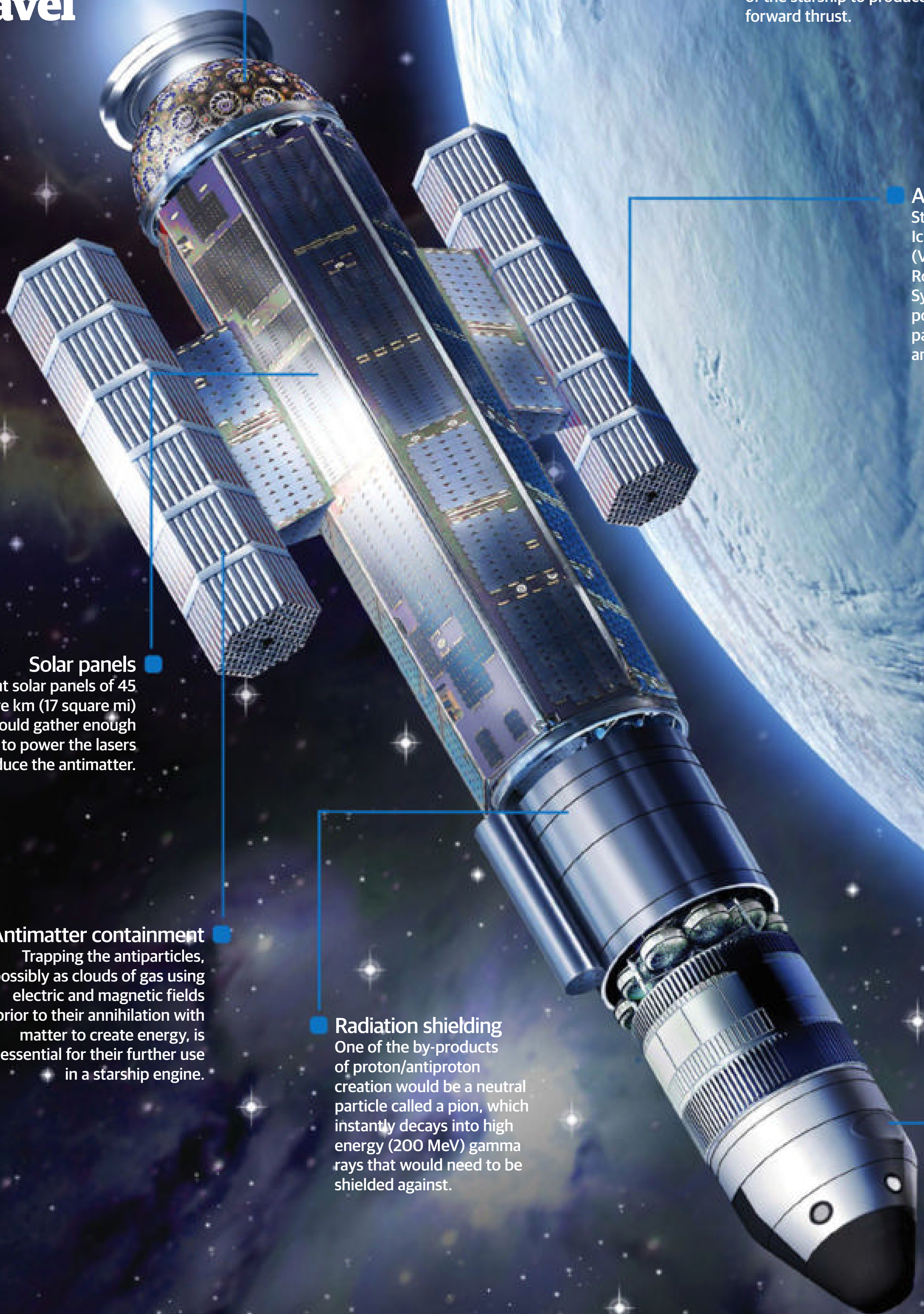
Fermi was actually expecting to see gamma rays from matter-antimatter annihilation near the centre of the galaxy, as was its European counterpart, the INTErnational Gamma-Ray Astrophysics Laboratory (INTEGRAL), which discovered a lopsided cloud of positrons in the galactic centre where annihilation is taking place and producing gamma rays with energies of around 511,000 electronvolts. Meanwhile the state-of-the-art Alpha Magnetic Spectrometer (AMS) on board the International Space Station is searching for antimatter in cosmic rays.

So it seems we are really starting to make headway in our quest to solve the mysteries of matter and antimatter and ultimately the grand mystery of why the matter-dominated universe as we know it exists at all.

"There's lots going on," says Hangst. "It's a very interesting time to be working in this field because we are getting more and more capabilities. At CERN we are studying antimatter to see if it behaves in the same way as matter; that's a long-term project. We're also looking for matter/antimatter asymmetry – does antimatter somehow behave different to what the laws of physics describe for matter? We'd like to study the spectrum of antihydrogen and compare that with what we have measured in hydrogen, or look at how antimatter behaves in a gravitational field. So those are the two big things: is antihydrogen quantum mechanically the same as hydrogen and does it fall up or down in gravity?"

The answers might unlock the secrets of the expanding universe and we could be extremely close to doing just that.

Interstellar antimatter travel



Magnetic nozzles
Powerful magnetic fields direct charged particles produced in the annihilation process out of the back of the starship to produce forward thrust.

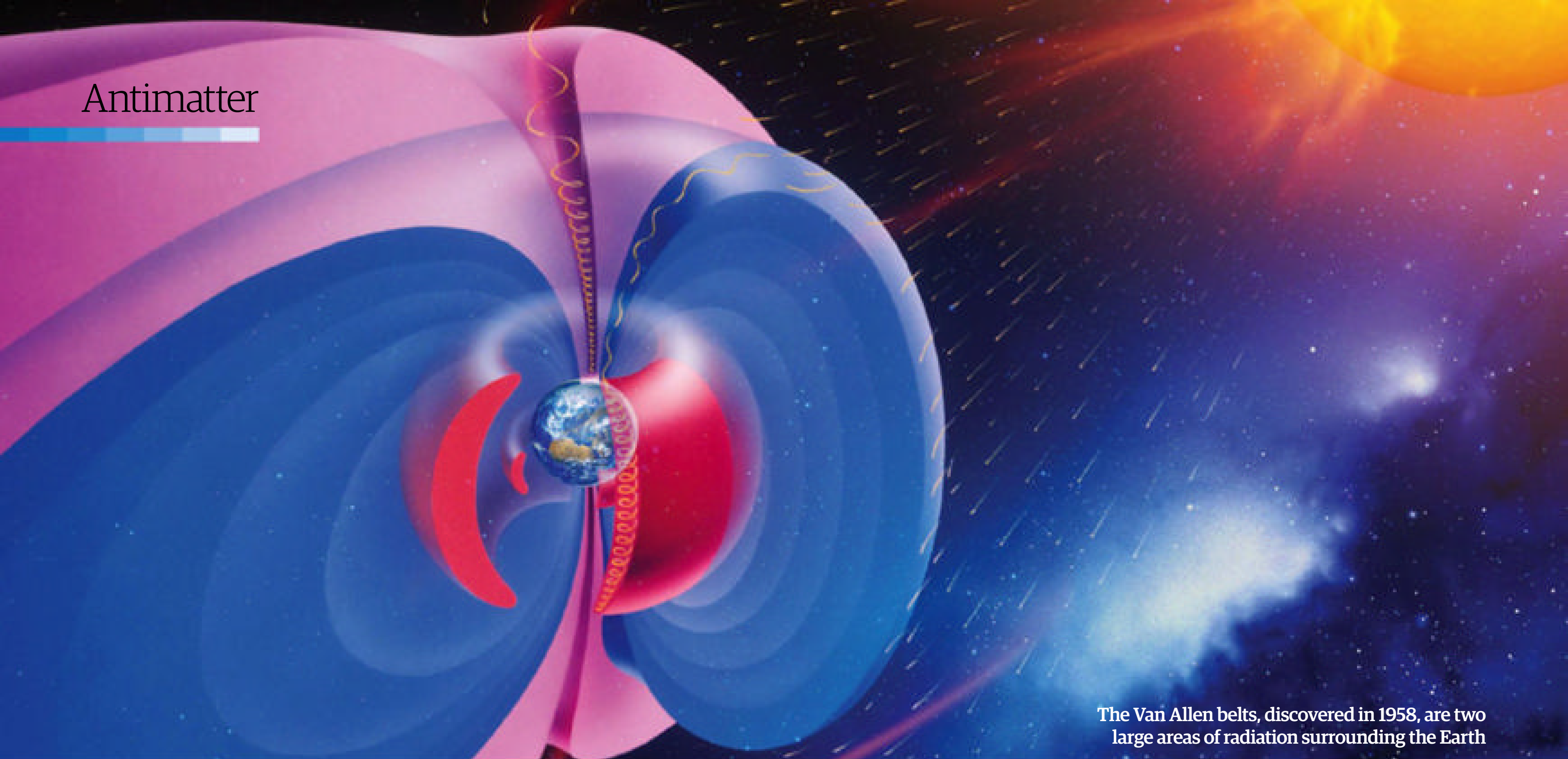
Antimatter creation
Starship designs such as Icarus Interstellar's VARIES (Vacuum to Antimatter-Rocket Interstellar Explorer System) proposes high-powered lasers to stimulate pair production of protons and antiprotons.

Solar panels
Giant solar panels of 45 square km (17 square mi) would gather enough energy to power the lasers to produce the antimatter.

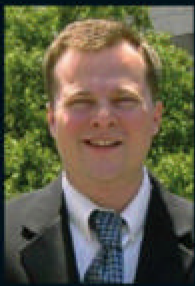
Antimatter containment
Trapping the antiparticles, possibly as clouds of gas using electric and magnetic fields prior to their annihilation with matter to create energy, is essential for their further use in a starship engine.

Radiation shielding
One of the by-products of proton/antiproton creation would be a neutral particle called a pion, which instantly decays into high energy (200 MeV) gamma rays that would need to be shielded against.

Payload
Instruments and crew quarters should reside as far away from the antimatter engine and storage tanks as possible to further reduce the effects of radiation.



The Van Allen belts, discovered in 1958, are two large areas of radiation surrounding the Earth



Looking for antimatter

All About Space talks to Jim Bickford of Draper Laboratory, Massachusetts, who found a belt of antimatter naturally occurring around Earth in one of our planet's Van Allen radiation belts

Scientists have spent billions building colliders that make a few micrograms of antimatter, yet you've found it around the Earth. How does it get there?

Antimatter forms when atomic particles travelling near the speed of light collide with one another and convert their energy of motion into matter. If they are travelling fast enough, a process called pair production creates a regular particle and its antiparticle by converting the kinetic energy of motion into mass. Outside of particle colliders, there are few places on Earth where there is enough energy to create antimatter. The Earth is constantly being bombarded by high energy cosmic rays which are formed outside the Solar System. When these cosmic rays strike our atmosphere, their energy of motion can be converted into antimatter. Most of it gets lost in the atmosphere, but a small fraction bounces back into space and gets caught in the Earth's magnetic field.

Is there enough antimatter to do anything with?

The amount of antimatter trapped around Earth is comparable to the amount of material in a speck of dust. This may sound like an incredibly small amount, but antimatter has unique properties which can make this useful for a number of applications. In particular, when matter and antimatter come into contact, they annihilate and their mass is converted into energy. Proposed applications include medical treatments, non-destructive material testing, fundamental physics and, of course, spacecraft propulsion. It would take hundreds of kilograms to propel a spacecraft to another star if used like a traditional rocket fuel.

Can we collect the antimatter?

The challenge has always been how to collect enough antimatter and then store it for use since it is spread so diffusely in space and it will annihilate when it comes into contact with ordinary matter. As part of my NASA Institute for Advance Concepts (NIAC) programme, we looked at how you could use large magnetic fields around spacecraft to funnel and collect the antimatter in space. The magnetic field can then be used to store what is collected until it is ready for use. The spacecraft could basically mine the antimatter from space and then use it to propel itself.

Do you think antimatter can be found around other planets?

The amount of antimatter around Earth is minuscule. However, there is significantly more in other parts of the Solar System. During the NIAC study, we evaluated each of the planets and found that Saturn was the best place for antimatter to collect. I originally assumed that the biggest planet, Jupiter, would have the most. However, Jupiter's magnetic field was too strong and it reduced the flux of cosmic rays from striking the atmosphere. The rings of Saturn, however, have just the right geometry and composition to create antiprotons, and the magnetic field works to trap it where it can then be collected.

Why is antimatter only in very short supply?

The unique properties of antimatter are what make it so difficult to create and store. It contains an incredible amount of energy, which also means that it takes an exorbitant amount of energy to create. It would take years of electrical output from a large nuclear power plant to create the energy contained in a kilogram of antimatter. Once you solve the production issue, you're left with the problem of how to store a material that will annihilate when it comes into contact with the walls of its container. When you calculate how inefficient it is to create and store, it becomes clear that it is impractical, if not impossible, to have large quantities of antimatter around.

Can studying antimatter help us to understand new things about the universe?

Research in this area is part of a broader framework that could help fundamental science and our understanding of the universe. Antimatter plays a central role in some of the Holy Grail problems of physics, such as the nature of dark matter and why matter dominates over antimatter.

> "We found that Saturn was the best place in the Solar System for antimatter to collect"