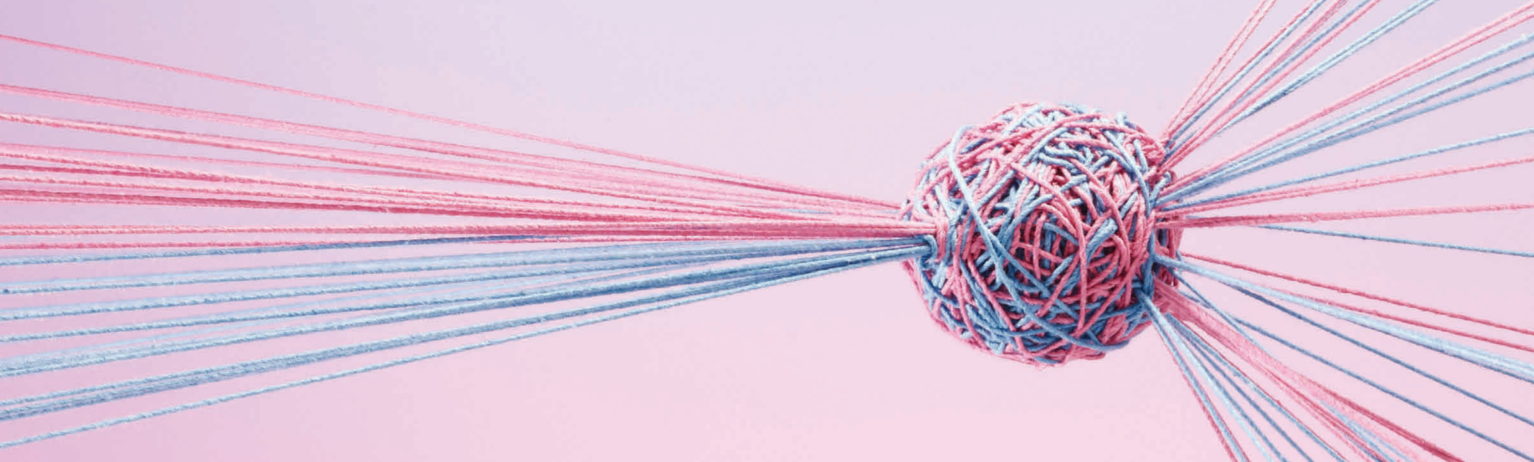
Opposite stuff

A perfect blend of matter and antimatter could guide us to limitless energy on earth, finds **Jon Cartwright**



A FRACTION of a second after the big bang, a new type of stuff flooded the universe. It was hot, it was self-destructive and it was weird. It wasn't matter. It wasn't antimatter. It was both.

This was the electron-positron plasma, a perfect balance of electrons and their antimatter equivalent. Within seconds, it had blinked itself out of existence: electrons and positrons annihilate on contact, their mass converting entirely into energy.

In some of the universe's biggest explosions, that process can be reversed, as pure energy spawns matter and antimatter. So we don't have to go all the way back to the big bang to understand the plasma – its hallmarks are all around us in these mysterious flashes lighting up the night sky.

Just recently, too, we've gone one better, replicating in the lab what normally takes place in an exploding star. That's no trivial undertaking, and raises the question of why we would want to. The reason is that the unique qualities of an electron-positron plasma makes it the ideal test bed for understanding the fundamental workings of more readily available plasmas. And if we can do that, there might be nothing stopping us from unlocking nuclear fusion, a theoretically limitless source of clean, safe power that could solve all our climate woes.

But back to basics first. The universe's ability to seemingly conjure an electron-positron plasma out of nothing arises from the equivalence of mass and energy, as given by Einstein's famous formula, $E = mc^2$. In the aftermath of the big bang, the universe was teeming with packets of energy in the form of photons of light. So long as a photon is more energetic than an electron and a positron combined, and so long as there is some sort of electromagnetic field present to administer the transaction, that photon can transform into an electron-positron pair – and vice-versa.

The electrons and positrons brought into being after the big bang didn't stick around for long. They cooled and then mostly turned back into photons, allowing protons and neutrons to bind into the first atomic nuclei and producing a gigantic flash of light.

What we've become increasingly confident about over the past decade or so is that this

STEPHEN LENTHALL/GALLERY STOCK

plasma-to-energy conversion is still happening today, inside slightly less big bangs taking place in space all around us. Take the events of an otherwise unremarkable Tuesday night in September 2008. In the greatest explosion anyone has ever witnessed, astronomers saw a flash of light amounting to thousands of times more energy than the sun produces in a year – released in a fraction of a second. Fortunately for us, it was more than 12 billion light years away.

Controlled detonation

The event was an example of a gamma-ray burst. Aside from the name, there isn't a lot about gamma-ray bursts that astronomers can tell you for certain. "Almost everything is mysterious," says Julian Osborne at the University of Leicester, UK, and the leader of a satellite mission called Swift, which studies them. There's no shortage of ideas, the leading one being that they rise from a particularly massive star spinning as it explodes into a supernova, channelling the energy of its blast in two diametrically opposite beams. Whatever the truth is, however, electron-positron plasmas are thought to lie at the heart of the mechanism, as electrons and positrons gyrate in magnetic fields or butt up against the interstellar medium, in either case giving off light.

These bursts aren't the only mysterious things that go bang in the night (see "Anniversary fireworks", page 34). Pulsars, which flash periodically like ghostly lighthouses for millions of years, are highly magnetic neutron stars that throw off photons from a tight region around the magnetic poles as they rotate. Fast radio bursts are also powerful, yet are over in less than the blink of an eye. All that is known about them is that they act like turbocharged pulsars, expelling all their photons in a single, ultra-short blast from a region that is 10 times smaller.

Again, we're fingering electron-positron plasma as the culprits. In pulsars and fast radio bursts, the plasmas could even be clustering into antenna-like structures that channel the radio waves into the cosmos. "One can't imagine what else could be involved, if not an electron-positron plasma," says Bing Zhang at the University of Nevada in Las Vegas.

Some want to find out for sure, but that's where our fortune becomes our › misfortune – the sources of these bursts are too far away. That's why a few years ago, a group led by Gianluca Sarri at Queen's University Belfast, UK, started work to produce an electron-positron plasma in the laboratory.

With a background in laser physics, Sarri knew that an ultra-short laser pulse could knock the electrons out of a rarefied cloud of atoms and propel them into a beam, at close to the speed of light. If such a beam struck a metal block, it would screech to a halt, projecting its energy in a new, highly energetic beam of photons. Sarri reasoned that here, amid the charged atomic nuclei of the metal, the photons should convert into a beam of electron-positron pairs. If he was right, this could be a way to simulate the universe's wildest events in the safety of the laboratory, and confirm their behaviour.

"Nuclear fusion could be the technology to meet all our energy needs"

In 2012, a first attempt at the laser facility of the University of Michigan got halfway there: a positron beam emerged, but it was drowned out by the metal's other electrons, and no plasma was produced. "We needed a bigger laser," says Sarri. Three years later, his group bagged the Astra Gemini laser system at the Rutherford Appleton Laboratory in the UK. This time, the detectors recorded not only equal numbers of electrons and positrons, but also stringy filamentation of the beam – the hallmark of a plasma's dancing self-interaction.

Such filaments should give rise to the magnetic fields that cause the electrons and positrons to morph into photons. Sarri hopes to reproduce those in a future experiment, but in the meantime he has begun investigating another idea: that a gamma-ray burst's appearance mostly results from its plasma rucking up against the interstellar medium, generating shock waves that fling photons outwards.

In August this year, Sarri and his colleagues sent their electron-positron plasma through a recreation of the interstellar medium and observed hints of unstable behaviour. The results are a tantalising glimpse of how lab experiments could probe high-energy astrophysics. Next, Sarri has set his sights on the forthcoming Extreme Light Infrastructure, a multi-laser facility based at four locations in Europe that he believes will properly simulate the process. "We hope to see shock waves," he says. "For us, this is the holy grail." Sarri believes that in the future, model pulsars and fast radio bursts could also be studied this way.

But there are reasons to covet an understanding of electron-positron plasma closer to home. At its heart, it's just another type of plasma: a gas heated up to such high temperatures that the negative and positive charges separate and float around side by side in a wraith-like fireball. Human-made plasmas are found in neon signs, fluorescent lights, modern television screens and, importantly, the gigantic experimental facilities hoping to crack nuclear fusion.

Clean, safe and running on abundantly available fuels such as hydrogen, nuclear fusion has been billed since the 1950s as the technology that will meet all humanity's energy needs. It requires a plasma made of electrons and the atomic nuclei, or ions, from which they have been stripped. When the plasma is sufficiently hot, the ions fuse, releasing huge amounts of nuclear energy. Yet progress has been painfully slow. The Joint European Torus (JET) in Culham, UK, can generate only 70 per cent of the power it requires to operate. ITER, the €15 billion next-generation fusion experiment under construction in the south of France, hopes to generate more power than it consumes by sometime in the late 2030s. It will take another reactor beyond that for commercially viable fusion.

Underlying this waiting game is the theory of plasma physics in fusion reactors, which is highly complex, thanks to the thousand-fold mismatch between electron and ion masses. This poses a challenge for theorists, says Thomas Sunn Pedersen of the Max Planck Institute for Plasma Physics in Germany: it can be impossible to know whether a prediction has failed because their simulation didn't

ANNIVERSARY FIREWORKS

Two of the universe's biggest types of explosion were first observed 50 years ago, and nearly mistaken for something else entirely. A gamma-ray burst was first detected in 1967 by the Vela satellites, which were put into orbit by the US to detect radiation from illicit nuclear weapons tests. Had the operators not noticed that the signals lacked the gradual fading of nuclear-weapon emission, the US and the Soviet Union may have found themselves in a diplomatic crisis. As it was, the operators filed the records away for nearly six years until they could be sure what they were dealing with.

The first observation of pulsars later that year was no less peculiar. When the UK astronomer Jocelyn Bell Burnell identified the oddly regular spikes of radio waves coming from the heavens, she naturally considered "little green men" as a possibility. "We did not really believe that we had picked up signals from another civilisation, but obviously the idea had crossed our minds," she recalled.

STEPHEN LENTHALL/GALLERY STOCK

work to enough decimal places, or whether there is some genuinely important physics that has been overlooked.

Enter the electron-positron plasma. If a regular electron-ion plasma is often called the fourth state of matter, after solids, liquids and gases, an electron-positron plasma is distinct enough to be a fifth. Bar having opposite electrical charge, positrons are identical to electrons in all respects, including their mass. Unlike lurching ions, then, positrons dance with electrons in perfect harmony: their plasma is inherently balanced. And that makes their behaviour much simpler to model.

Pedersen likens an electron-positron plasma to the hydrogen atom, whose unrivalled simplicity allowed physicists in the early 20th century to test their theories of quantum mechanics, without fear of any complicating factors. Today, largely based on these efforts, quantum mechanics is a supremely successful theory on which much of modern technology is based. Could electron-positron plasmas be a similar testing ground for plasma physics? "If you make a prediction about an electron-positron plasma, it must be right," says Pedersen. "If it isn't we'll say, 'Ah ha! There's something else here we really need to revisit.'"

"I think he's right," says Steve Cowley, a plasma physicist at the University of Oxford and former chief executive of the UK Atomic Energy Authority. "Electron-positron plasmas won't probe everything, but if you want to compute a plasma in a basic sense, they would be much simpler."

For decades now, Pedersen has been trying to build a plasma reservoir capable of keeping a cloud of electrons and positrons alive. To build it, he has borrowed the same basic technique found in traditional electron-ion plasma research: magnetic confinement. If you design the magnetic fields in the right way, the charged particles can be kept levitating far away from the walls of a container, where they would be swiftly annihilated.

Taming a monster

That all sounds simple enough, but there's a problem: getting the electrons and positrons inside. Electrons are easy to come by, but Pedersen is sourcing the positrons from a nuclear reactor at the Technical University of Munich, and these take a while to accumulate. Unfortunately, the magnetic field used to sustain the nascent plasma also prevents new particles from entering the trap. "We need to open a door, shove the particles in, and shut the door again," says Pedersen.

Problems like this are not easy to solve, but a sizeable grant from the European Research Council this year has given him confidence that a perfect plasma is within reach. In their latest experiments, he and his colleagues have found that by applying a steady voltage across the trap, new electrons and positrons can be encouraged to drift inside without disturbing the magnetic field that contains the others. "We could have the first plasma in two years," he says optimistically.

Pedersen expects his electron-positron plasma to live long enough to betray its rich inner life. One of the key questions he hopes to answer is how long it will take the plasma to escape its confinement and perish on the trap's walls. Everything we know about plasmas so far tells us that it should last several minutes. If the electron-positron plasma turns out to be more volatile than our theories predict, however, it would mean some fundamental physics has been missing all along. Account for that, and it's possible that the more complicated plasmas required for fusion could suddenly make sense too. Despite the decades he's invested into making this hypothetical state of matter a reality, Pedersen is hoping it doesn't stick around too long. "Predictions say that the plasma will be stable," he says. "But that would be boring." ■

Jon Cartwright is a freelance journalist based in Bristol, UK

LOVE-HATE RELATIONSHIPS

An electron-positron plasma isn't the only form of matter that relies on seemingly impossible pairings (see main story). In fact, electrons and positrons can get together in individual pairs to make "positronium", orbiting atom-style around their combined centre of mass and perhaps shedding light on the reason the universe seems to have more matter than antimatter.

Quarks – which make up the protons and neutrons inside atomic nuclei – can also unite with their opposite equivalents. Such is the case with heavy and surprisingly long-lived quark-antiquark pairs of "quarkonia". Since their discovery in the 1970s, quarkonia have given insights into features of the strong nuclear force, which binds quarks together.

Meanwhile, hypothetical Majorana particles could be their own antiparticles, capable of annihilating themselves under the right conditions. Although fundamental Majorana particles are yet to be observed, this year Kang Wang at the University of California, Los Angeles, and others claimed to observe Majorana-like behaviour in the collective motions of multiple particles inside specially layered materials. The strange properties of the Majorana quasiparticles could one day be exploited for quantum computing.