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Trouble at Earth's first dark matter factory

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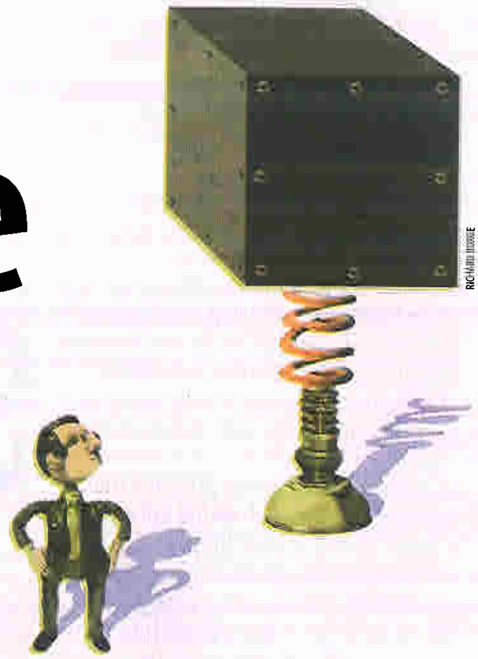
Let there be dark



Why hunt for dark matter when you can make it instead? **Stephen Battersby** reports

GIOVANNI CANTATORE is feeling rather troubled. On the face of it, he shouldn't be: his experimental results suggest that he and his colleagues have succeeded in creating dark matter, and, although this is the stuff that is thought to make up about one-fifth of the mass of the universe, no one has ever managed to see so much as a particle of it before. Detecting it would be a major breakthrough; working out how to make it in the laboratory should put him and his colleagues in the running for a Nobel prize.

And yet Cantatore, who works at the Italian institute for nuclear physics in Trieste, is troubled. Why? Because there's something about his team's results that makes no sense.

Their dark matter particles – called axions – aren't behaving as they should. They seem to be endowed with a property that means they should have sucked the life out of the sun billions of years ago. Plainly this has not happened, so what is going on? "It is very disturbing," says Cantatore.

Axions might have been created when photons collided in the early moments after the big bang. Their existence was first invoked by theorists needing a particle to patch up a flaw in the theory of the strong force that binds atomic nuclei together. But it soon turned out that axions could fill another hole: they are among the lightest particles around and yet there could be so many of them that they outweigh all the visible matter in the universe. That makes them a candidate for explaining the anomaly of the universe's "missing mass" (see "Dark horses", page 37). Cantatore's laboratory, which is in Legnaro, about 150 kilometres from Trieste, could be the world's first dark matter factory.

"The experiment could be the world's first dark matter factory"

If, that is, the Italians can get to the bottom of their axions' behaviour. It was Cantatore's Trieste colleague Emilio Zavattini who came up with the idea behind the Legnaro experiment. Decades ago he suggested that axions could be created in the lab by firing a laser through a magnetic field. If photons really do interact to produce axions, laser photons that happen to be polarised parallel to the field have a small chance of being converted into axions. The axions will escape, but the loss of those converted photons twists the overall polarisation of the laser beam.

Cantatore's team has been looking for this twist using a magnet that produces a field of 5 tesla, 100,000 times stronger than the Earth's magnetic field. Last year they reported success. When a laser beam was bounced back and forth through the field 44,000 times, its polarisation had rotated by a few parts in a hundred million.

Instead of filling the researchers with joy, however, the result so unnerved them that they spent the next three years checking it before reporting it. That rotation, slight though it sounds, is altogether too much for comfort. It means that far more axions were being created than the theory predicts. The Italian group seems to have discovered a ▶

Dark horses

Observations of the ways stars and galaxies move suggest that the universe contains massive particles that we simply can't see. This is "dark matter". Two kinds of hypothetical particle pop out of theories describing the nature of dark matter: axions and weakly interacting massive particles. WIMPs are thought to be big and heavy, probably hundreds of times the weight of a proton, and their existence is predicted by several untested theories, including supersymmetry. So far, WIMPs have attracted most of the attention of dark matter researchers – but it need not be that way. "Axions are just as theoretically compelling a dark matter candidate as WIMPs," says Pierre Sikivie of the University of Florida in Gainesville. "WIMPs are just more fashionable at the moment."

If our galaxy's dark-matter halo is made of axions, there should be a lot of them about – about 10,000 billion in every cubic centimetre of space. Like WIMPS, however, theory says that axions are maddeningly difficult to detect because they interact only very weakly with ordinary matter.

temperature falls, these particles will combine and form axions." He has calculated that more energy would be stolen by axions than comes out in photons, so the sun would still be snuffed out. Kleban has also tried devising theoretical models to fix the problem by making a readily forming axion that is star-safe, but all of his attempts have failed. "I think it's pretty difficult to come up with one that works," he says.

Others are slightly more hopeful. Particle physicist Ann Nelson of the University of Washington in Seattle is one – but she has a caveat. "I don't think it would be hard to come up with a consistent theory, but it would be ugly," she says.

Maybe physicists should accept that nature is ugly. But maybe not just yet – it is still entirely possible that Cantatore's troubling measurement is a mistake. Adrian Melissinos of the University of Rochester in New York thinks it is far more likely that the Legnaro result is just a mirage, some flaw in the experimental set-up. "My opinion is that it is absolutely wrong," he says.

Melissinos's confidence comes from the fact that he worked with Cantatore on a similar experiment at Brookhaven National Laboratory in Upton, New York, in the 1980s. That experiment saw no sign of axions, despite being more sensitive than the set-up at Legnaro. However, it had one small disadvantage. The Brookhaven experiment was only suited to seeing axions with a mass of less than 0.8 millielectronvolts. Cantatore's experiment is sensitive to axions a shade heavier, at 1 millielectronvolt. And the mass of the detected axions appears to be right on that upper threshold, out of reach of the Brookhaven team.

> "A consistent theory would not be hard but it would be ugly"

The best way to resolve the controversy and to discover whether mutant axions really are flying about the universe is an experiment called photon regeneration, also known by the rather Zen-like term of "invisible light shining through walls". The idea is to aim a laser like the one in Legnaro through a magnet at a solid wall and to put another magnet on the other side. The wall will stop the laser beam from passing through, unless some of its light is turned into axions, which should fly straight through the wall.

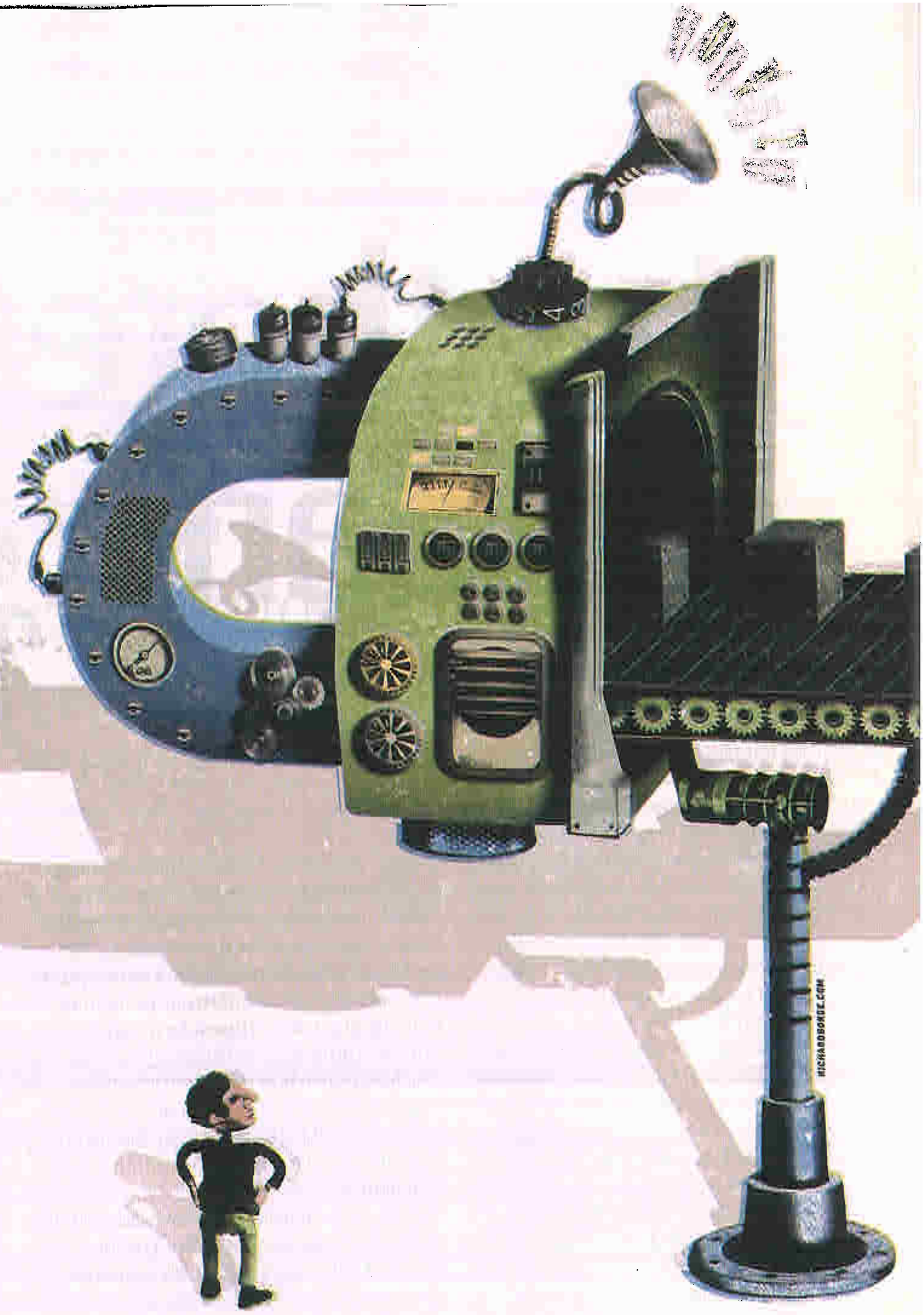
"If the Legnaro result is correct, there will be hundreds of millions of axion-like particles crossing the wall every second," says Paul Rabadan of the Institute for Advanced Study in Princeton. When they then pass through the magnetic field on the other side of the wall, a few of them should turn back into photons with exactly the same frequency as the original laser beam. "It would be an irrefutable signal of the existence of this particle," says Rabadan.

Cantatore's team is planning a photon regeneration experiment this year. An independent test is to be carried out at the DESY laboratory in Hamburg, Germany, by early 2007, and others are planned by CERN and by a collaboration between the universities of Toulouse and Lyon in France. If any of these labs find that invisible light does shine through walls, it will be a bombshell; physicists will be faced with trying to explain how these impossible particles can exist. They might find that the mutant axion leads to a fundamental change in our picture of reality, perhaps an unwelcome, ugly one. Still, at least the sun will carry on shining. ●

mutant axion. And it has some rather undesirable properties.

For a start, the characteristics of this new particle mean that it cannot cure the problems with the strong force. The axion was originally thought up to fix a problem with quantum chromodynamics (QCD), the theory that describes the behaviour of the quarks inside protons and neutrons, and of the gluons that stick them together. Without axions, certain reactions involving gluons would look different depending on whether time runs forwards or backwards, and that has never been observed in experiments. Yet the mutant axion has the wrong properties to fix this.

Worse, its effects should have shown up in other experiments. All sorts of observations – including our own existence – seem to show that this particle doesn't exist. An axion that is formed so easily in the lab would not only have been formed soon after the big bang, but should also be produced in huge quantities as photons collide in the sun's core. The axions would fly straight out of the sun and into deep space, which would have drained all the sun's fusion energy after only a few thousand years. The same is true of every star: Cantatore's mutant axion would make the universe a pretty dark and lifeless place.



Invisible light

So is Cantatore sure he has not simply made some experimental error? Not at all. "At the moment we are only reporting an anomalous observation," he says. "You should keep in mind the possibility that it is an instrumental effect." Indeed, he says, there is a puzzling amount of variation in the observed rotation that the team cannot explain.

But the fact remains that the effect just won't go away, whatever the researchers do. Recently, they tried swapping the old infrared laser beam for a green laser in case the wavelength of the light had something to do with it, but they are still seeing the twist in the laser beam's polarisation. Though Cantatore shies away from claiming to have proved the existence of the particle, the effect certainly seems real enough.

Leslie Rosenberg of the University of Washington in Seattle, another physicist trying to detect dark matter axions, also thinks there could well be something in it. "Although it would be premature to throw your hands in the air and cry hallelujah, it would be foolish to ignore this result," he says. "It really is a head-scratcher."

If the axion is real, then it must be a truly bizarre object, far beyond the bounds of the standard model of particle physics. "It would be remarkable and a major discovery," says Massachusetts Institute of Technology physicist Frank Wilczek, who co-wrote the paper that first predicted the axion, naming the particle after a brand of detergent because it cleaned up the problem with QCD.

A few people have already tried to reconcile the Italian measurement with other evidence. One idea comes from Eduard Massó and Javier Redondo of the University of Barcelona in Spain. They suggest that the particle detected at Legnaro could be made of two as yet unknown quark-like particles that are loosely bound together. This fragile composite could form easily in the cool environment of Cantatore's lab, but not in the turbulent furnace of a stellar core or a supernova, so it would not suck out all their energy. "You need something very exotic, either our idea or something else," Massó says. "If everything is confirmed, this will be a little revolution." Massó's composite axion is probably the nearest anyone has got to a solution so far, but it is rather messy. It needs not only the new constituent particles, but also a new fundamental force to bind them together, and all the properties of this composite creation have to be carefully chosen.

Even then the hypothesis may not work, according to Matthew Kleban of the Institute for Advanced Study in Princeton. "Inside the sun there would be a hot soup of all the new particles that compose the axion," he says. "As you move out from the centre and the