Dark forces at work

Are we immersed in a shadowy world of dark matter and hidden forces? **Anil Ananthaswamy** investigates

IT IS 3.30am on 26 December 2007 in McMurdo, Antarctica. The crew at the long-duration balloon facility have stayed up all night in sub-zero temperatures, waiting for the winds to subside. Finally, the gigantic balloon lifts off. Filled with about a million cubic metres of helium, it soars high into the stratosphere carrying an experiment called ATIC.

For 19 days, ATIC circled the South Pole, studying cosmic rays coming from space. Then, nearly a year later, the ATIC team made a stunning announcement: they found that more high-energy electrons had left their mark on the experiment than expected. That might not sound like much, but the result is remarkable because it might be a telltale sign of dark matter, the invisible stuff thought to make up about 85 per cent of matter in the universe.

And it's not the only one. Just months before, an Italian-led collaboration reported that their satellite-based experiment, called PAMELA, had seen a similar excess of electrons, along with an excess of positrons. Add to this earlier results from gamma-ray satellites and experiments searching for dark matter here on Earth, and suddenly we have an abundance of new clues about dark matter. "It is a very exciting time to be doing dark-matter physics," says Dan Hooper, a physicist at the Fermi National Laboratory in Batavia, Illinois.

The bonanza of evidence suggests that dark matter might be far more complicated than we had ever imagined. For starters, the theoretician's favourite dark-matter candidate is falling out of favour, with the latest experiments making the case for new, exotic varieties of dark matter. If they are right, we could be living next to a "hidden sector", an unseen aspect of the cosmos that exists all around us and includes a new force of nature.

Such hidden worlds might sound strange, but they emerge naturally from complex theories such as string theory, which attempts to mesh together the very small and the very large. Hidden worlds may, literally, be all around us. They could, in theory, be populated by a rich menagerie of particles and have their own forces. Yet we would be unaware of their existence because the particles interact extremely weakly with the familiar matter of our universe. Of late, physicists have been taking seriously the idea that particles from such hidden sectors could be dark matter.

We know precious little about dark matter, but we do know that its gravity is what keeps galaxies and clusters of galaxies from flying apart, despite the staggering speeds of the individual stars and galaxies within them. We also know that it must be made of particles that are massive and interact only very weakly with their surroundings. Anything that matches this description is known as a weakly interacting massive particle.

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Finding these WIMPs is easier said than done, so scientists use indirect ways of looking for them. Wherever they accumulate in large numbers, they should collide and destroy each other, leaving behind particles such as electrons, protons, positrons and antiprotons. This can confuse the search for dark matter, as the same particles are produced when cosmic rays smash into interstellar dust.

Take the Alpha Magnetic Spectrometer (AMS), which flew on NASA's space shuttle Discovery in 1998. It detected more positrons in space than were expected from cosmic rays. So did the High Energy Antimatter Telescope (HEAT), which was lofted by balloons in 1994, 1995 and 2000. "But their error bars were not good enough to know whether there was anything interesting or not," says physicist Neal Weiner of New York University.

Now that both ATIC and PAMELA are confirming the excess, the results can no longer be discounted. Astrophysicists have so far struggled to explain the surplus electrons and positrons. If they fail, then the most likely source is the annihilation of WIMPs, each with a mass about 600 to 1000 times as great as a proton.

So far, so exciting. But researchers have run into problems when they try to identify what kind of particle WIMPs might be. Since the 1980s, the front runner has been a stable particle called the neutralino, which popped out of attempts to fix the standard model of particle physics. This theoretical particle is massive enough, interacts weakly with normal matter and, most importantly, its density in the early universe would have been just right to give us the dark matter we observe today.

However, the ATIC and PAMELA results place stringent constraints on the nature of dark matter, which makes things very difficult for annihilating neutralinos to be the answer. According to our best understanding of neutralinos, they should produce a few electrons with higher energies and many more with low energies. ATIC has found the opposite. Not only that, but the annihilation should also generate antiprotons, something PAMELA has seen no evidence of. "Neutralinos just do a lousy job with this data set," says Weiner.

Given this rap against neutralinos, many, including the ATIC team, are leaning towards another candidate: something called Kaluza-Klein particles (*Nature*, vol 456, p 362). These arise in theories from the 1930s that attempt to unify gravity with ›

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electromagnetism by positing the presence of an extra dimension of space.

According to the theories, known particles such as electrons can enter the small, hidden extra dimension where they can move at different speeds. The energy of motion in the extra dimension manifests itself as mass in our world. So an electron moving in a higher dimension would appear to us as a much heavier Kaluza-Klein electron, except directly detecting one is impossible. These heavy particles are short-lived and decay to lighter varieties which, like neutralinos, are stable and have the right properties to be dark matter.

The lightest Kaluza-Klein particle has another attractive property. When these WIMPs smash into each other and annihilate, their mass energy transforms into oppositely charged particles like electrons and positrons, and muons and antimuons, whose energy matches the ATIC and PAMELA results. What's more, the Kaluza-Klein particles are expected to produce far fewer antiprotons than neutralino annihilations which, again, squares with the recent experiments. "The thing I like about the Kaluza-Klein particle is that it wasn't invented to explain dark matter," says Hooper.

If researchers can prove the existence of Kaluza-Klein particles, they would confirm theories that say there are more dimensions to space than the simple left and right, forwards and backwards, up and down we know about.

However, the dark matter windfall could be telling us that the universe is even stranger than we suspected. Researchers have gone back to other anomalous sightings, including observations from the INTEGRAL gamma-ray satellite launched by the European Space Agency in 2002.

INTEGRAL detected very bright emissions of photons with precisely 511 kiloelectronvolts (keV) of energy in the Milky Way. You would expect to find such photons when electrons and positrons annihilate each other. "The question is how many positrons are there, and where do they come from?" says Weiner. "Their distribution doesn't look like what you would expect from astrophysical sources," such as supernovae or microquasars.

So were these emissions coming from dark matter too? In 2007, Weiner and Doug Finkbeiner of Harvard University tackled the INTEGRAL results. They calculated that if WIMPs could enter an excited state when they smacked into each other, then they could emit 511 keV photons as they settled back into their ground states.

But to make this work, Weiner and Finkbeiner had to assume that the WIMPs interacted via a new force. Everyday forces like electromagnetism are transmitted by force-carrying particles that dart between charged particles. In the same way, Weiner and Finkbeiner calculated that their new force needs a hypothetical particle that weighs about the same as a proton and shuttles back and forth between WIMPs only (*Physical Review D*, vol 76, p 083519). This means that the standard model particles do not feel this force. Dark matter, it seems, could belong to a hidden sector of the universe.

Hidden sectors have been studied by Matthew Strassler of Rutgers University in Piscataway, New Jersey, and Kathryn Zurek of Fermilab. "When we talk of hidden worlds, what we are saying is that there could be a sector just as complex as the visible sector, but it's shielded from us because the way it communicates with electrons, nuclei and ordinary stuff is very weak," says Zurek.

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There are hints that such a hidden sector could be the source of dark matter. It came to light last October when Weiner and Finkbeiner joined up with theorists Nima Arkani-Hamed at the Institute for Advanced Study in Princeton and Tracy Slatyer at Harvard University.

When Weiner and Finkbeiner first proposed dark forces to explain the INTEGRAL anomaly, their idea was greeted with polite scepticism. Then came the ATIC and PAMELA results. To reconcile all the findings, the team revisited the idea and, to their astonishment, found that the new force more than comes in handy, pulling WIMPs together and increasing the likelihood that they will collide and annihilate.

It turns out that the dark force boosts the annihilation rate of slow-moving WIMPs by two to three orders of magnitude, as required to explain the ATIC and PAMELA results. Yet it has no effect on much faster particles that filled the early universe. All this means that there should still be plenty of WIMPs around today that we should be able to see annihilating each other.

The calculations by Arkani-Hamed and colleagues also show that when the WIMPs annihilate they can produce the dark-force carriers. Because these new particles weigh about the same as a proton, they are too light to decay into a proton and an antiproton. So instead they decay into lighter electrons and positrons.

Weiner says his team were excited by the findings because the same thing that boosted the number of annihilations is the same thing that gives a surplus of electrons and positrons – without any antiprotons. In one fell swoop, their "unified theory" describes the results from ATIC, PAMELA and INTEGRAL

Dark-matter detectives

Several experiments have found disparate strands of evidence for dark matter.

Balloon | Space shuttle | Satellite | Underground

EXPERIMENT	STUDIED	FOUND
ATIC (Balloon) Advanced Thin Ionization Calorimeter	Cosmic rays in atmosphere at South Pole	Excess high-energy electrons.
PAMELA (Satellite) Payload for Antimatter/Matter Exploration and Light-nuclei Astrophysics	Cosmic rays in space	Excess high-energy electrons and positrons. No surplus antiprotons
AMS (Space shuttle) Alpha Magnetic Spectrometer	Cosmic rays in space	Excess positrons (inconclusive)
HEAT (Balloon) High Energy Antimatter Telescope	Cosmic rays in atmosphere	Excess positrons (inconclusive)
INTEGRAL (Satellite) International Gamma-Ray Astrophysics Laboratory	Gamma rays in space	Photons with energy of 511 keV
DAMA (Underground) Dark Matter	Direct search for weakly interacting massive particles (WIMPs)	Seasonal variation interpreted as evidence for WIMPs (controversial)
CDMS (Underground) Cryogenic Dark Matter Search	Direct search for WIMPs	No signal


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(*Physical Review D,* vol 79, p 014015).

It also solves another dark matter mystery. In April 2008, a team searching for dark matter deep inside the Gran Sasso Mountain in Italy reported an increase in the energy of particles hitting their detectors every June compared with December over a period of 11 years. The DAMA/LIBRA collaboration attributes their finding to Earth's motion through a sea of WIMPs that surrounds the Milky Way.

But none of the other experiments looking for direct hits by dark matter, such as the CDMS detector at the Soudan Underground Laboratory in Minnesota, have seen anything. Because of this, most physicists dismiss the DAMA/LIBRA finding.

So which results are correct? Both, says Weiner, who claims that the unified theory can explain the discrepancy between the DAMA/LIBRA and CDMS results. The traditional view of dark matter envisages particles of the same type bouncing off nuclei much like billiard balls. The CDMS team assumes this is what will happen inside their detector. But if dark matter is more complex, as Weiner's team claims, then the collisions with nuclei can instead create excited states of dark matter.

This scenario favours detectors that use material with heavier nuclei. DAMA/LIBRA contains iodine, which is considerably heavier than the germanium and silicon inside CDMS, and so DAMA/LIBRA is more likely to detect dark matter, says Weiner.

Hooper is impressed with the work, yet remains sceptical. "The thing that is appealing about their model is that it kills many birds with one stone," he says. "But it is a pretty carefully designed stone to do all this killing."

Weiner is more optimistic. "Physics is always about trying to find a single explanation for multiple phenomena," he says. "It certainly doesn't guarantee that this idea is right, but some types of theories tend to want to work, and this theory seems like it wants to work."

While this unified theory has attracted tremendous attention since it was published, there are stumbling blocks. If it is correct, the high density of dark matter at the centre of the galaxy means that there should be a lot of annihilation there – and lots of electrons and positrons. We would expect to see these charged particles spiralling around magnetic fields, producing a pronounced excess of synchrotron radiation. "And you don't see that," says Lars Bergström, a physicist at Stockholm University in Sweden, who has examined detailed radio telescope measurements near the centre of the Milky Way. So how do we tell right from wrong?

Other experiments will help. One is NASA's Fermi satellite, launched last year, which could confirm with a high degree of accuracy the excess of electrons over a wide range in energy. If WIMPs really are 600 times as massive as protons, we would expect to see an abrupt drop in the number of electrons above a certain energy threshold. The HESS detector in Namibia, which measures photons given off by high-energy electrons striking the atmosphere, should also be sensitive to this drop. If it detects such a thing, it will be a stunning signal as it cannot be produced by astrophysical sources.

Fermi will also be able to see gamma rays that are produced when WIMPs annihilate. The energies of these rays should differentiate Kaluza-Klein states from neutralinos. Fermi will even be able to pinpoint spots in the sky from where the gamma-rays are coming. If it detects a big nearby clump, or clumps, neutralinos will be back in favour as the claims against them assume that dark matter is evenly spread throughout the galactic halo.

It might take evidence from closer to home to seal the case, though. Pauline Gagnon, an experimental physicist working at the CERN particle physics laboratory near Geneva, Switzerland, is talking to Weiner about verifying their unified theory. Preliminary calculations suggest that the Large Hadron Collider could produce the new force carrier, which would eventually decay into an electron and a positron. Gagnon is working with others to see how these signals would show up in the giant ATLAS experiment.

All hopes are on Fermi finding indirect clues to the nature of dark matter. "If we then find that particles with the same sort of mass and properties are being created at the LHC, I think the last sceptic would concede that this is what we are looking at out there in the universe," says Hooper. ■

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