PPARC

The search for

WIMPs

The UK's dark matter experiment at Boulby

The Boulby mine in North Yorkshire

Dark secrets at the bottom of a mine

UK RESEARCHERS WORKING IN A UNIQUE DEEP UNDERGROUND SITE ARE LEADING THE WAY TO DISCOVER WHAT THE UNIVERSE IS MADE OF

Perched on the edge of the North York Moors National Park, not far from the sea, are the surface buildings of one of the deepest mines in Europe. Since the 1970s, Cleveland Potash Ltd has been mining potash and salt at Boulby near Whitby to a depth of 1300 metres – creating a warren of caverns and tunnels that even extend 5 kilometres under the North Sea.

This hot, dusty underground environment is not only the site of a successful mining operation, however. It is also houses a new laboratory complex where some of the most sensitive and delicate investigations in understanding the Universe are carried out. Here, physicists can fine-tune their ingenious instruments to detect the existence of exotic subatomic particles called WIMPs.

WIMPs (short for weakly interacting massive particles) may be the answer to a major mystery about the Universe: what is actually holding it together? For the past 70 years, astronomers have realised that the stars and galaxies we can see in the night sky cannot account for all the matter in the cosmos. The way stars swirl round in their galactic islands, and galaxies cluster together, indicates that there must be a huge amount of invisible 'dark matter' controlling their movements by the pull of its gravity. In fact, at least 90 per cent of the Universe must consist of this unknown matter. Cosmologists also think that dark matter is needed to explain how galaxies and galaxy clusters formed and why the Universe looks the way it does.

What could the dark matter be? The most likely explanation is that it consists of a type of fundamental particle that

Cleveland Potash Ltd

Mining potash in the mine

(Top) programming the DRIFT dark matter detector in the Boulby mine to begin a new run; (right) part of the new JIF experimental area

emerged after the Big Bang (the fireball explosion in which the Universe was created) along with the other particles making up everyday matter. Fortunately, our theories about these building blocks of nature, and how they were created, can accommodate the idea of a massive particle which feels the force of gravity – but interacts only weakly with ordinary matter.

Spot the WIMP

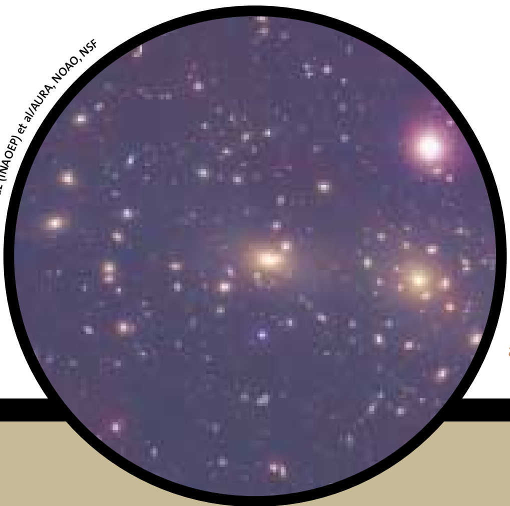
Although billions of WIMPs are probably passing through you every second, they hardly interact with ordinary matter so are extremely difficult to detect. Occasionally, though, they do knock into the nuclei of atoms, and it is possible to design instruments that detect the effects of these rare collisions. A group of UK physicists has been developing world-leading experiments to catch WIMPS passing through the Earth from space. Because the measurements are so delicate, they must be shielded from interfering effects of other particles coming from space such as cosmic rays, and from the surroundings such as gamma-rays, electrons and alpha particles (helium nuclei).

This is where the Boulby mine comes in. Its deep subterranean caverns offer such protection. Furthermore, the salt rock itself gives out little radioactivity, and is safe and easy to excavate. When the researchers first started to consider how to carry out the experiments in the 1980s, they thought they would have to go to one of the few underground sites around the world already used for particle experiments. Learning that the UK had, at that time, the deepest mine in Europe, the team approached the mine's managers who agreed to accommodate the dark matter project. They enlarged an existing cavern and laid on electrical power and ventilation. Cleveland Potash has remained an enthusiastic supporter ever since.

The underground laboratory

When UK researchers first considered carrying out a search for WIMPs they were not sure how it could be done. After testing out many technologies, they came up with a series of original detector designs that are extremely sensitive and can pick out signals expected from WIMPs against those from background radiation. Three detectors are already installed at Boulby together with support laboratories.

More recently, a further major excavation has been completed for a new laboratory covering a further 1000 square metres, thanks to a £3 million award from the Government's Joint Infrastructure Fund to the University of Sheffield with partner CLRC. The underground site, equipped with control rooms, clean rooms and workshops, will be the base for the **Boulby Underground Laboratory for Dark Matter Research**. ■



O. Lopez-Cruz (INAOEP) et al/AURA, NOAO, NSF

The Coma cluster of galaxies which move so fast that they must contain large amounts of dark matter to account for their dynamics

Spiral galaxy NGC 628 taken with Gemini North. The speeds of stars orbiting in such galaxies (like our own Milky Way) indicate the presence of dark matter

How do we know that dark matter exists?

All matter succumbs to the force of gravity, the strength of attraction depending on the mass according to Newton's law. It's therefore possible to calculate the masses of distant objects such as stars and galaxies by measuring their relative motions under the effect of gravity. This is what the astronomer Fritz Zwicky did, as early as 1933, when he analysed the orbits of a group of galaxies called the Coma Cluster. He found that they were moving so fast that they ought to have been flung apart.

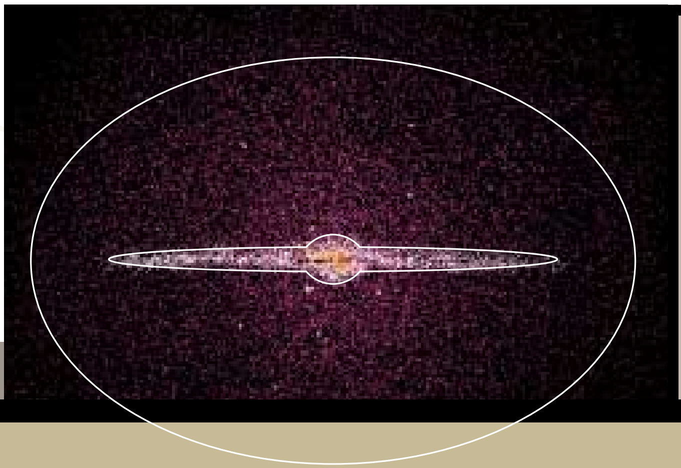
Similar results emerge when trying to measure the speeds of stars orbiting in galaxies such as our own Milky Way. The outer stars are moving much too fast for the amount of mass estimated from what we can actually see through telescopes. In fact, 10 times as much matter is needed to explain the results, and scientists now think that a typical galaxy must be embedded in a vast halo of invisible matter.

Extensive observations have re-inforced the conclusion that at least 90 per cent of the Universe is invisible. Although seemingly an uncomfortable result, cosmologists are reasonably happy with the idea because the presence of dark matter also helps to account for the evolution of cosmic structure after the Big Bang when space and time came into existence. Their computer models, showing possible ways in which the Universe could have evolved, depend upon the gravitational effects of dark matter to 'seed' the spidery network of galaxy clusters and filaments recently mapped by powerful telescopes.

Cosmological importance

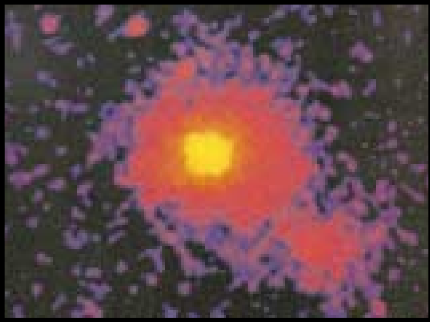
Another important ingredient in the cosmological picture is the geometry of space. This concept comes from Einstein's General Relativity theory which proposes that the Universe can be thought of in terms of four dimensions, three of space and one of time. Space is thus like a three-dimensional membrane that can be either curved or flat. The presence of a mass causes it to bend giving us the force of gravity. Certain theories describing the Universe's primordial stages – which have been recently backed up by observations – suggest that space is, in fact, flat. However, this requires a certain 'critical' density of matter. Again, the existence of a large amount of dark matter is needed to contribute to this critical density.

Einstein's theory also predicts a more direct, visible way in which dark matter can reveal itself. Light is deflected when it passes through a gravitational field. This means that light reaching us from a galaxy (or star) can be bent by the gravity of an intervening mass, such as a lump of dark matter, to give a distorted image, or even multiple images, of the galaxy. This 'gravitational lensing' effect thus allows astronomers to observe the presence of dark matter. Several research groups are now mapping the distribution of dark matter on a cosmic scale. ■



An end-on view of a spiral galaxy showing the possible distribution of dark matter in a halo around the central core

So, what is dark matter?



(Top) the Coma cluster as seen by the X-ray satellite ROSAT. (Above) gravitational lensing in a galaxy cluster revealed by the Hubble Space Telescope; the optical distortions may be caused by intervening dark matter

A range of candidates has been suggested for the missing mass from black holes to exotic particles. One possibility is that the dark-matter halos of galaxies could simply be ordinary matter such as hydrogen and helium constituted from protons and neutrons (baryons) – but not in the form of luminous stars. Suggestions include clouds of cold gas, or bodies that aren't emitting light. The latter might be brown dwarfs – small clumps of hydrogen gas, perhaps the size of Jupiter, generating insufficient gravity to set off the nuclear reactions that make a real star.

Dark matter could also be black holes, objects so dense that their gravity prevents even light escaping. Black holes could form when supermassive stars go supernova at the end of their nuclear-burning lifespan and collapse under their own weight.

Astronomers have been looking for these **Massive Compact Halo Objects** – MACHOs – over the past few years but with disappointing results. Searches using the technique of gravitational lensing described opposite, in the halos of our Galaxy and nearby galaxies, have found only enough MACHOS to account for less than 20 per cent of galactic halo matter.

Cosmology also predicts that it is highly unlikely that the missing matter is composed of baryons. Calculations on how much of the lightest elements, hydrogen, helium and lithium, formed in the aftermath of the Big Bang, suggest that the amount of baryons produced was woefully inadequate.

Fortunately, particle physicists have come to the rescue. The theorists have proposed several fundamental particles, which are not baryons, that could be dark matter candidates. One such particle is the **neutrino** which would have been produced in copious amounts in the early Universe. Although standard particle theory predicts that neutrinos are massless, recent neutrino-detection experiments are starting to suggest that neutrinos can oscillate between three types, which can happen only if they have mass. However, this is probably not enough to solve the dark matter problem.

Another particle that might have been made in large enough amounts is the **axion**. This is also a light neutral particle which interacts only weakly with ordinary matter. An American collaboration has built a detector to detect the microwave photons that axions should decay into in a strong magnetic field.

A more interesting candidate is the **WIMP**, which arises from a theoretical extension to the current particle picture called supersymmetry. This idea proposes that the elementary particles we now know of have a heavier super-partner. A leading WIMP candidate is the lightest neutral supersymmetrical particle, the neutralino.

WIMPs are the more likely to be the main source of dark matter for cosmological reasons. In the early Universe, the heavy-weight WIMPs would be moving much more slowly than the light neutrinos, and as such could have brought about galaxy formation at an early enough stage to explain the cosmological structure we see today. It is possible that the missing mass could be a cocktail of 'cold dark matter' (WIMPs) mixed with a little 'hot dark matter' (neutrinos) and an added smidgen of nonluminous baryonic matter.

Inspecting the ZEPLIN I experiment

How to detect a WIMP

Every second, a million WIMPs pass through each square centimetre of the Earth, travelling at hundreds of kilometres per second, but very few interact with matter. Less than one WIMP a day will collide with one atomic nucleus in a kilogram of material, knocking it backwards. This is the principle of detecting WIMPs. The energy released from the recoiling atom can be measured and analysed in various ways.

Any detector must be carefully shielded from interactions with other particles from the surroundings that might produce a similar signal. As well as being shielded from cosmic rays by being situated deep underground, the detector must be constructed from materials low in radioactive impurities and encased in a dense shield to filter out any radiation from the surrounding rock. In the Boulby mine, the WIMP detectors are contained in massive lead or copper 'castles', up to 30 centimetres thick, which reduce the radiation by a factor of a million.

The dark matter team at Boulby currently employs three WIMP detectors using different materials. One detector is **ZEPLIN I** which uses 4 kilograms of liquid xenon. The energy from the recoil of a xenon nucleus causes atoms in the material to ionise and release photons of light (scintillation). The light is then detected by three photomultiplier tubes which amplify the signal. The nuclear recoils can be separated from any other signals, for instance, electron recoils caused by gamma-rays, by carrying out careful statistical analysis.

Another sensitive detector is an array of sodium iodide crystals (NaI) called **NAIAD** (NaI Advanced Array Detector) which also produces a scintillation signal. It is currently investigating a claim by another dark matter team using a similar but larger detector in the Gran Sasso tunnel in Italy that they have detected WIMPs.

An even more subtle experiment will detect whether the nuclear recoil signal is genuinely due to WIMPs in the Galaxy. As the Earth moves through the Galaxy, we should see a wind of WIMPs blowing from the direction of this motion. The average direction of the recoils measured should match this. Because the Earth is rotating, there should also be a daily modulation of the signal which could not be mimicked by any background signal. The **DRIFT** (Directional Recoil Identification From Tracks) detector, recently installed as part of the new laboratory, will use 1 cubic metre of low-pressure gas in which individual events produce ionisation tracks that can then be imaged.

Future WIMP detectors

The new area will eventually house more advanced dark matter detectors. Successors to **ZEPLIN I** – **ZEPLIN II** and **ZEPLIN III** – are currently being constructed. They will be able to reject more of the background signals thus giving greater sensitivity. These experiments will then be followed by **ZEPLIN Max**, which will be even more sensitive, containing 1 tonne of the detector material (250 times as much xenon as in ZEPLIN I). Two further directional experiments have also been designed, **DRIFT II** and **DRIFT III**. These are multi-module-based and will be 50 and 1000 times as sensitive to WIMP direction respectively. ■

(Left) A researcher polishes a sodium iodide crystal ready for installation as part of the NAIAD experiment. (Right and inset) the DRIFT experiment to detect the direction of WIMPs

The UK Dark Matter Collaboration

Researchers from several UK institutions make up the UK Dark Matter Collaboration which is funded by PPARC to work on experiments at Boulby. The collaboration involves research groups from **Sheffield University** (led by Professor Neil Spooner), from the **Rutherford Appleton Laboratory** in Oxfordshire (led by Dr Nigel Smith), **Imperial College of Science, Technology and Medicine** (led by Professor Tim Sumner), and the University of Edinburgh (Dr Alex Murphy).

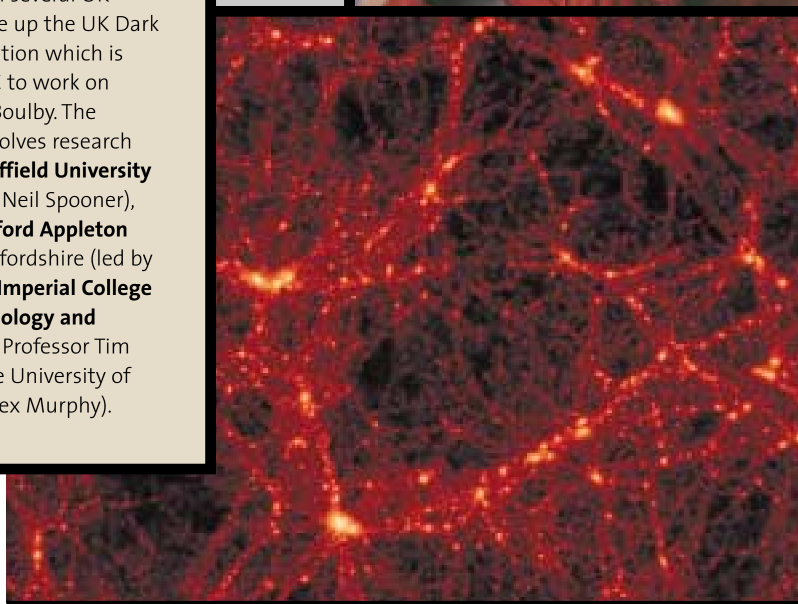
International collaboration

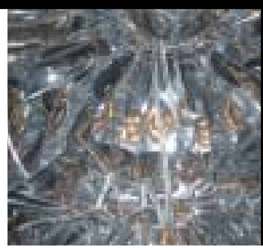
The ZEPLIN and DRIFT experiments are international collaborations (ZEPLIN: **University of California at Los Angeles, University of Turin**, the **Institute for Theoretical and Experimental Physics** in Moscow, and **Texas A&M University**; DRIFT: **Temple University, Occidental College,Wayne State University** and the **Lawrence Livermore National Laboratory**).

Industrial involvement

Detector design has involved input from several UK companies, and has received five PIPSS awards and several CASE awards (these awards stipulate industrial collaboration). The photomultipliers used to observe the scintillation light were developed in conjunction with a UK company based near London, which makes photomultipliers – **Electron Tubes Ltd** – to ensure that they were made from materials with low levels of radioisotopes but were high in efficiency. The Collaboration has also worked with two UK companies making novel scintillator materials – **Hilger Analytical Ltd** in Kent and **Zinsser Analytic Ltd** in Maidenhead, Berkshire.

Particularly significant is the ongoing contribution of the host mining company, **Cleveland Potash** (owned by ICL), which in the early stages provided the original site and other resources such as electricity. The company continues to support the UK's only underground laboratory.





(Top) one of the dark matter researchers examines a photomultiplier from the NAIAD detector used in the dark matter experiment. (Centre) a computer simulation by the Virgo Consortium of the evolution of the Universe assuming the presence of dark matter. (Bottom) Part of the ZEPLIN I detector

Other experiments

There are several research collaborations searching for WIMPs plus several experiments looking for axions. A number of experiments are searching for WIMPs: the UK Dark Matter Collaboration, the UK-supported CRESST experiment and the Italian/Chinese DAMA collaboration – located in the Gran Sasso laboratory in a mountain tunnel in Italy, the Cryogenic Dark Matter Search (CDMS) at Stanford University in California and the Soudan Mine, and the Edelweiss cryogenic experiment in the Frejus tunnel in France.

Opportunities for the UK

Identifying dark matter is considered one of the most important tasks in fundamental physics. Other experiments in this area are being set up around the world, and over the next few years the race to discover the main constituent of the Universe will become intense. The UK Dark Matter Collaboration was one of the first groups working on this problem, developing ingenious new technology in the process. The collaboration is now building links with the Institute for Computational Cosmology (ICC) and the Institute for Particle Physics Phenomenology (IPPP) at Durham University. With the construction of the new Boulby Underground Laboratory for Dark Matter research the UK has a golden opportunity to build on early successes and experience to maintain a leading position in this growing area of astroparticle physics. ■

Dark matter information

More information can be obtained from the following sources:

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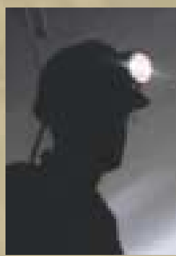
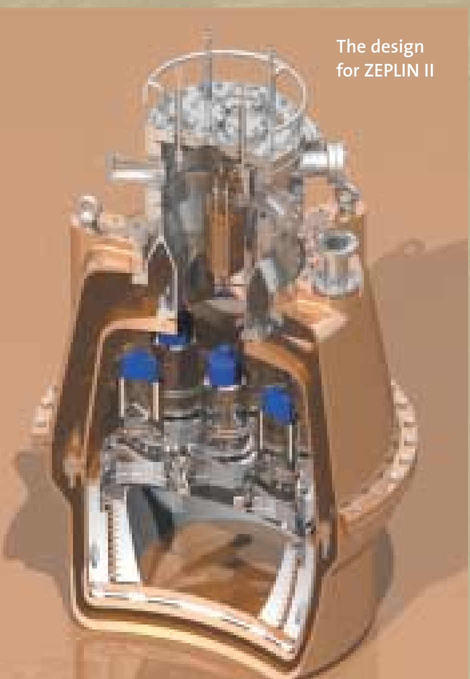


UKDMC website:
http:hepwww.rl.ac.uk/ukdmc/ukdmc.html


The design for ZEPLIN II

Particle Physics and Astronomy Research Council

The Particle Physics and Astronomy Research Council (PPARC) is the UK's strategic investment agency. PPARC delivers world-leading science, technologies and people.

PPARC provides research grants and studentships to scientists in UK universities, and ensures that they have access to world-class facilities. PPARC manages UK scientific membership of international bodies such as the European Laboratory for Particle Physics (CERN), European Space Agency (ESA) and the European Southern Observatory, which also offer UK business access to commercial opportunities in Europe.

PPARC coordinates UK involvement in overseas telescopes on La Palma and Hawaii, in Australia and Chile, and manages the UK Astronomy Technology Centre at the Royal Observatory Edinburgh and the MERLIN/VLBI National Facility.

The technologies developed by PPARC research can be found in business, defence, industry and education. There are direct benefits to society in terms of development of new materials and products, raising the skills base, and maintaining the UK as a world-leader in these fields.

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Boulby Underground Laboratory
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