

DARK MATTER Dan Hooper

NewScientist

UNEVEN BACKGROUND

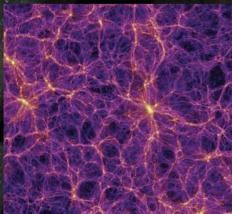
Although we still can't see the stuff itself, we see evidence for dark matter everywhere we look, for example in the radiation known as the cosmic microwave background (CMB), which was created in the infancy of the universe.

About 380,000 years after the big bang, the temperature of the universe dropped below about 3000 degrees kelvin, making it possible for the first time for atoms to form (see diagram, right). The transition from disconnected nuclei and electrons to electrically neutral atoms released a huge amount of energy in the form of light, and the expansion of the universe has since stretched this light to microwave wavelengths. This radiation today fills all of space, a relic of our universe's hot youth.

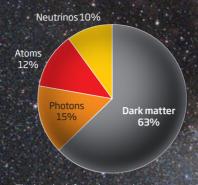
By studying the patterns of slightly hotter and colder patches in the CMB, we have been able to learn a great deal about our universe's history and composition. Among other things, these variations in the CMB tell us how matter was distributed throughout space in the early universe. Because dark matter began clumping under the influence of gravity earlier than normal matter did (see "The invisible hand", below right), its influence can be seen in numerous small hot and cold patches, each covering an angle in the sky of 0.25 degrees or so.

The pattern of these spots even allows us to determine how much dark matter must be present. It turns out that for every gram of stuff that we can see in the cosmos there must be 4 or 5 grams that we can't. That doesn't even include another, perhaps even more mysterious, substance whose existence can be inferred from the CMB: dark energy, a force that seems to be causing our universe to expand ever faster. Totting up all the mass and energy in the universe, dark energy trumps normal matter and dark matter combined by a factor of almost 3 to 1.

Dark matter simulations accurately reproduce the large-scale cosmos

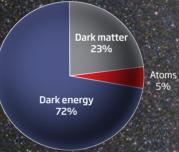


UNIVERSE 380,000 YEARS OLD



The imprint left on the cosmic microwave background shows that dark matter accounted for most of the mass and energy of the early universe

MODERN UNIVERSE



Today, both dark matter and visible matter seem to be dwarfed by dark energy, an even more mysterious substance accelerating the expansion of the universe

THE INVISIBLE HAND

Even if dark matter weren't needed to prevent galaxies flying apart, supercomputer simulations suggest that the cosmos would look very different if it didn't exist. These simulations track the movement of billions of particles through cosmic time, with the aim of better understanding why the universe has ended up the way it has.

When atoms in a gas of ordinary matter are compressed, they collide more frequently. This interaction tends to push the atoms apart and so hinders gravity from compressing the gas any more. Dark matter particles, on the other hand, interact with each other only feebly and so clump much more readily. Simulations that embody these properties show that as the universe expanded and evolved, the first structures to form would have been clumps, or "halos", of dark matter.

The first dark matter halos to form were probably about as massive as the Earth, but far more diffuse. Over time, they began to merge and became steadily larger. Eventually, some became massive enough to attract large quantities of hydrogen, helium and other conventional matter - the seeds of the first stars and galaxies.

The agreement between the shapes and sizes of the structures derived in dark-matter simulations and those observed in our universe is striking (see picture, left). That leaves little doubt that dark matter is not only real, but also that it formed the nurseries in which galaxies such as our own Milky Way formed.

DARK MATTER: THE EVIDENCE

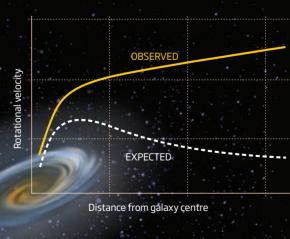
It is an embarrassing time to be a cosmologist. Only a couple of decades ago, we thought we understood the substances that fill the universe. No more. We now know that the atoms making up everything visible in the cosmos – from galaxies to planets to clouds of interstellar gas and dust - represent less than about 20 per cent of the total matter out there. The remaining 80 per cent is mysterious "dark matter", invisible to conventional telescopes. But if we can't see it, how can we be so sure it's there?



GALAXIES IN A SPIN

We can't weigh the sun or a planet directly. Instead, we determine its mass by measuring how its gravitational pull influences the motion of objects around it.

In the same way, it should be possible to measure the mass of a galaxy, or even a cluster of galaxies, by observing how fast stars or other objects move around it. In 1933, the Swiss astronomer Fritz Zwicky (pictured, right), working at the California Institute of Technology in Pasadena, applied this principle to the motion of galaxies that make up the Coma cluster, a group of over 1000 galaxies some 300 million light years from us. He found that the individual galaxies were zipping round far too rapidly for their gravity to keep them bound together in a cluster. By rights they should have



Stars near the edge of galaxies are travelling too fast to be held in orbit merely by the gravity of the matter we can see in the galactic centre been flying off in different directions.

Zwicky's puzzling results didn't get much attention until the late 1960s, when the astronomer Vera Rubin at the Carnegie Institution in Washington DC measured the Doppler shift of clouds of hydrogen gas in several distant galaxies. This showed that the speeds at which the clouds were orbiting the centre of their galaxies seemed to require far more mass than could be accounted for by visible material (see diagram, near left).

The discrepancy between the amount of visible matter and the strength of gravity is most pronounced in some of the very smallest galaxies, known as dwarf spheroidals. These objects contain as few as tens or hundreds of thousands of stars, but produce a gravitational attraction equivalent to tens of millions times the mass of our sun. Even our own Milky Way galaxy generates a gravitational pull of an object of roughly 800 billion solar masses, despite containing a total visible mass of only a couple of hundred million suns.

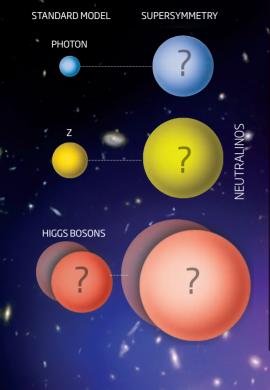
Without dark matter, the very existence of many apparently stable galaxies would defy the laws of physics. The fact that they do exist remains among the most compelling reasons to think that there must be more to the cosmos than meets the eye.







In supersymmetry theories, neutralinos pop up as heavier partners of the photon, the Z boson that mediates the strong nuclear force and the as-yet undiscovered Higgs bosons



AN ELEGANT SYMMETRY

Few ideas currently enthral particle physicists more than supersymmetry. The theory is mathematically elegant and could solve some persistent problems – including, perhaps, the nature of dark matter.

In our world, there are two classes of particles: fermions and bosons. Fermions are particles such as electrons, neutrinos and quarks that make up what we normally think of as matter. Bosons are the particles responsible for transmitting the forces of nature. The electromagnetic force, for example, is nothing more than bosons - photons, in this case - shuttling back and forth between electrically charged particles.

Supersymmetry postulates that fermions and bosons cannot exist independently of each other: for each type of fermion, a type of boson with many of the same properties must also exist. The electron, for example, has an as-yet undiscovered bosonic partner called a selectron. Similarly, the photon should have a fermionic analogue known as a photino.

Among the many new particles predicted by supersymmetry is one that is likely to be stable and have all the characteristics required of a viable dark matter candidate. It is the lightest version of a class of particle known as a neutralino. Supersymmetric theories contain at least four neutralinos, which are quantum-mechanical mixtures of the superpartners of the photon, the Z boson that transmits the weak nuclear force and as-yet undiscovered Higgs bosons. Tantalisingly, if neutralinos do exist, the lightest version would probably have been produced in the first seconds after the big bang in quantities similar to what is needed to account for the dark matter in our universe today.

There is, of course, a catch: to date, no one has seen a supersymmetric particle. Physicists generally suspect that the superpartner particles – if they exist – are considerably heavier than their ordinary counterparts, making them very difficult to create or discover in experiments. Huge particle accelerators such as the Large Hadron Collider are on the case (see "In the accelerator", page vi), but until we have hard evidence, the supersymmetry hypothesis will continue to be just that – a hypothesis.

Did we get gravity wrong?

Is dark matter strictly necessary? In 1983, the Israeli physicist Mordehai Milgrom suggested that the higher-than-expected speeds of stars moving around galaxies might be explained another way - if gravity worked differently than predicted by the theories of Newton or Einstein. In particular, he pointed out that the observed galactic rotations could be explained if Newton's second law of motion - force equals mass times acceleration, or *F* = *ma* - were modified to make the force of gravity proportional to the square of the acceleration at very low accelerations.

In recent years, however, Milgrom's proposal called MOND, for "modified Newtonian dynamics" has suffered some serious setbacks. In particular, it has not managed to explain convincingly the dynamics of galaxies within clusters. Observations in 2006 revealed a pair of merging galaxy clusters, known collectively as the Bullet cluster, whose motion indicated that their gravity was not centred on the gas and stars, as would be expected according to MOND. That suggests dark matter has shifted the centre of gravity elsewhere (see picture, page vi).

While some cosmologists don't yet accept that the evidence against MOND is conclusive, most no longer consider it to be a viable alternative to dark matter.

"Proposals for dark matter's identity range from heavy neutrinos to some truly bizarre suggestions"

WHAT IS DARK MATTER?

The short answer is that we don't know what dark matter consists of. It must be invisible, or at least very faint, so it cannot be made of anything that significantly radiates, reflects or absorbs light. That rules out conventional atom-based matter. Other observations provide further clues to its identity.

MACHO OR WIMP?

We once thought that dark matter might be made up of large objects such as black holes or exotic types of faint stars - neutron stars or white dwarfs - that are nearly invisible to our telescopes. But observations seem to have ruled out these "massive astrophysical compact halo objects", or MACHOS.

The concentrated gravity of a MACHO would deflect passing light on its way to us from distant stars. We do observe such "gravitational lensing" effects, but only often enough for MACHOs to account for at most a few per cent of the mass we do not see. So most cosmologists now think instead that we are submerged in a sea of dark matter a gas of "weakly interacting massive particles", or WIMPs - that pervades the entire volume of our galaxy, including our solar system.



The only particles we know about that are both stable and do not carry electric charge - and so do not interact with light - are the elusive entities known as neutrinos. Might they be dark matter?

Unfortunately not. Neutrinos are very light and fast-moving, or "hot", and so resist gravity's efforts to clump them together. For galaxies and even larger structures to have formed with their observed shapes and sizes, dark matter particles must have been moving slowly, far below the speed of light, over much of the universe's history. Dark matter must be quite "cold".

What might this lethargic gas of invisible matter be made of? None of the many types of particles discovered over the past century fits the bill: not electrons, quarks, muons, Z bosons or any other known form of matter. Dark matter must be something completely new. Proposals for dark

> matter's identity range from heavy, neutrino-like particles, to ultra-light and cold species of matter known as axions, to truly bizarre possibilities such as particles that are moving through extra dimensions of space.

Dozens of different possibilities have been suggested over the years. To many physicists, however, there is a clear favourite among them: particles predicted by a class of theories that goes by the name of supersymmetry (see "An elegant symmetry", opposite page).



Hubble Space Telescope

observations were used

to produce this 3D map

of cosmic dark matter

The CERN Axion Solar Telescope looks for one dark matter candidate

NA CAVECA / D. MA SSEV/CALTECU



UP IN THE AIR

While some search for dark matter particles deep underground, others look to space for telltale signs of the elusive stuff's existence. Here, the aim is not to see the particles directly, but to spy the hugely energetic but otherwise ordinary forms of matter and energy that can be created when massive dark matter particles interact and annihilate each other.

To spot the products of such interactions we need telescopes - not of the sort that focus light with lenses or mirrors, but ones tuned to detect everything from gamma rays to antimatter, and even neutrinos from our galaxy and beyond. In recent years, a few of these unconventional telescopes have picked up signals tantalisingly similar to those predicted to come from dark matter annihilations.

In 2008, for example, the satelliteborne PAMELA experiment discovered that a surprisingly high proportion of the cosmic rays travelling through space were not ordinary matter, but antimatter. That might be down to dark matter annihilations - or it might come from well known sources of antimatter in our galaxy, such as the fast-rotating neutron stars known as pulsars. NASA's Fermi Gamma-Ray Space Telescope has also recently seen a bright source of gamma rays from the centre of our galaxy that very much looks like the signal expected from annihilating dark matter particles.

These may be the first glimpses of dark matter, but more time and better data will be needed to know for sure.

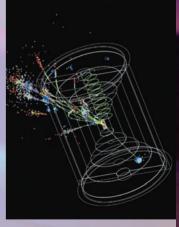
The Bullet cluster: visible matter, pink; inferred position of dark matter, blue. But can we see its dark matter directly? "To spy dark matter, detectors must be highly sensitive and made of the purest materials"

IN THE ACCELERATOR

Detecting the dark matter particles that nature supplies may prove to be a tough order for our current technologies. So why not make them ourselves? That's one of the aims of the world's most energetic particle smasher, the Large Hadron Collider (LHC), housed at the CERN particle physics laboratory near Geneva, Switzerland.

The LHC uses powerful magnets to accelerate beams of protons around a 27-kilometre tunnel beneath Switzerland and France, until they are moving at about 99.999999 per cent of the speed of light. Inside enormous, sports-hall-sized particle detectors, these enormously energetic protons collide head-on, mimicking the kind of interactions that took place at the ultra-high temperatures pervading the universe an instant after the big bang.

Among the massive particles created in these hugely energetic reactions might be supersymmetric particles and other exotic beasts that could fit the description of dark matter. Because particles of dark matter by their nature do not interact very much with



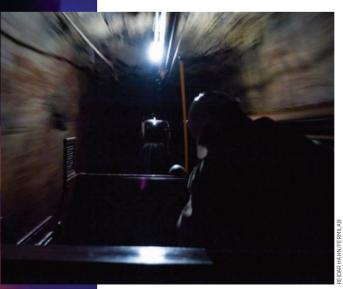
the ordinary material of a particle detector, the LHC will not be able to detect them directly. But experiments such as ATLAS and CMS could infer their presence from imbalances in the energy and momentum being carried away from collisions like the one depicted above.

THE HUNT FOR DARK MATTER

Because dark matter particles interact only very feebly with ordinary matter, they will inevitably be difficult to spot against the noisy backdrop of our world. Nonetheless, a range of new and sensitive detectors – in wildly diverse environments – aim to get them into their sights.



Dark matter detectors occupy sterile conditions in deep mines to shield against cosmic rays



DOWN THE MINE

Imagine standing on a busy street corner, listening out for the sound of a pin dropping on to the street. That's akin to the task physicists have taken on in their attempts to detect the impact of dark matter particles.

The incessant motion of atoms and the bombardment of Earth by the energetic particles of normal matter from space called cosmic rays together make for a very noisy backdrop. Couple that with dark matter's disinclination to interact with anything normal, and detectors must be amazingly sensitive and made from the purest of materials.

To shield against cosmic rays, dark matter hunters have gone deep underground, setting up detectors in mines in Canada, Italy, the UK, the US and elsewhere. One of these underground experiments, DAMA/LIBRA at the Gran Sasso National Laboratory in central Italy, uses a quarter-tonne detector made of sodium iodide to sense the impact of passing dark matter particles. For the past 10 years, DAMA/LIBRA has been picking up a signal that varies regularly with the seasons – slightly higher in summer and lower in winter – which is exactly what would be expected if our planet is moving through a sea of dark matter particles on its way around the sun.

DAMA/LIBRA's results have long been controversial, in part because other experiments have failed to reproduce them. But in February 2010 the Coherent Germanium Neutrino Technology (CoGeNT) experiment in the Soudan mine in northern Minnesota saw a signal in its small crystalline germanium target, which is expected to be especially sensitive to lighter dark matter particles. If the signal is from dark matter then about 100 particles of dark matter collided with the CoGeNT detector over a period of about two months. If with more data this signal shows the kind of seasonal variation reported by DAMA/LIBRA, that will start to look like convincing evidence that dark matter particles are actually being detected.

Whatever happens, the sensitivity of such dark matter experiments has been improving by an impressive factor of 10 every two years or so. If dark matter is ever going to be directly detected, it is likely to be detected soon.



Dan Hooper

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WHAT HAPPENS NEXT?

Dark matter is at a crossroads. Few problems have received more attention from physicists and astronomers in recent years than trying to discover what it is and how it works. So far, there are few concrete facts, just educated guesses.

That could soon change. Any of the types of dark matter searches – direct detection in deep mines, indirect detection with space telescopes, or the Large Hadron Collider – could be near a breakthrough. Are CoGeNT and DAMA/LIBRA seeing dark matter? Is dark matter producing the gamma rays that the Fermi space telescope has observed coming from the centre of our galaxy? There is as yet no consensus on these questions, but time and more data should provide answers.

If dark matter is in fact made up of "weakly interactive massive particles" (WIMPs), such as particles similar to those predicted by supersymmetry, success could be just around the corner. On the other hand, if no such signals appear in the coming decade, physicists are going to have to throw out much of what they think they know about dark matter and dream up new possibilities. Perhaps dark matter is entirely inert, and does not interact at all with normal matter. If so, it will never be detectable by any of the experiments physicists have been designing – a dark matter hunter's worst nightmare.

If I were to make a bet, I would put my money on the first unambiguous evidence for particle dark matter appearing within the next few years. Once those detections start taking place, we will begin to shed light on dark matter's properties in detail. If 2011 is an embarrassing time to be a cosmologist, it is an exciting one too.

RECOMMENDED READING

Particle Dark Matter: Observations, Models and Searches edited by Gianfranco Bertone (Cambridge University Press, 2010)

Einstein's Telescope: The hunt for dark matter and dark energy in the universe by Evalyn Gates (W.W. Norton, 2009)

Dark Cosmos: In search of our universe's missing mass and energy by Dan Hooper (Smithsonian Books, 2006)

The Fifth Essence by Lawrence Krauss (Basic Books, 1991)

"Particle dark matter: evidence, candidates and constraints" by Gianfranco Bertone, Dan Hooper and Joseph Silk, arxiv.org/abs/ hep-ph/0404175

"TASI 2008 Lectures on Dark Matter" by Dan Hooper, arxiv.org/abs/0901.4090

Cover image: Jim Richardson/Getty/NGS