Phys 10

Primack

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Most of the matter in the universe appears to be invisible, and the stuff it's made of may be unlike anything we know.

The Case of the Dark Matter

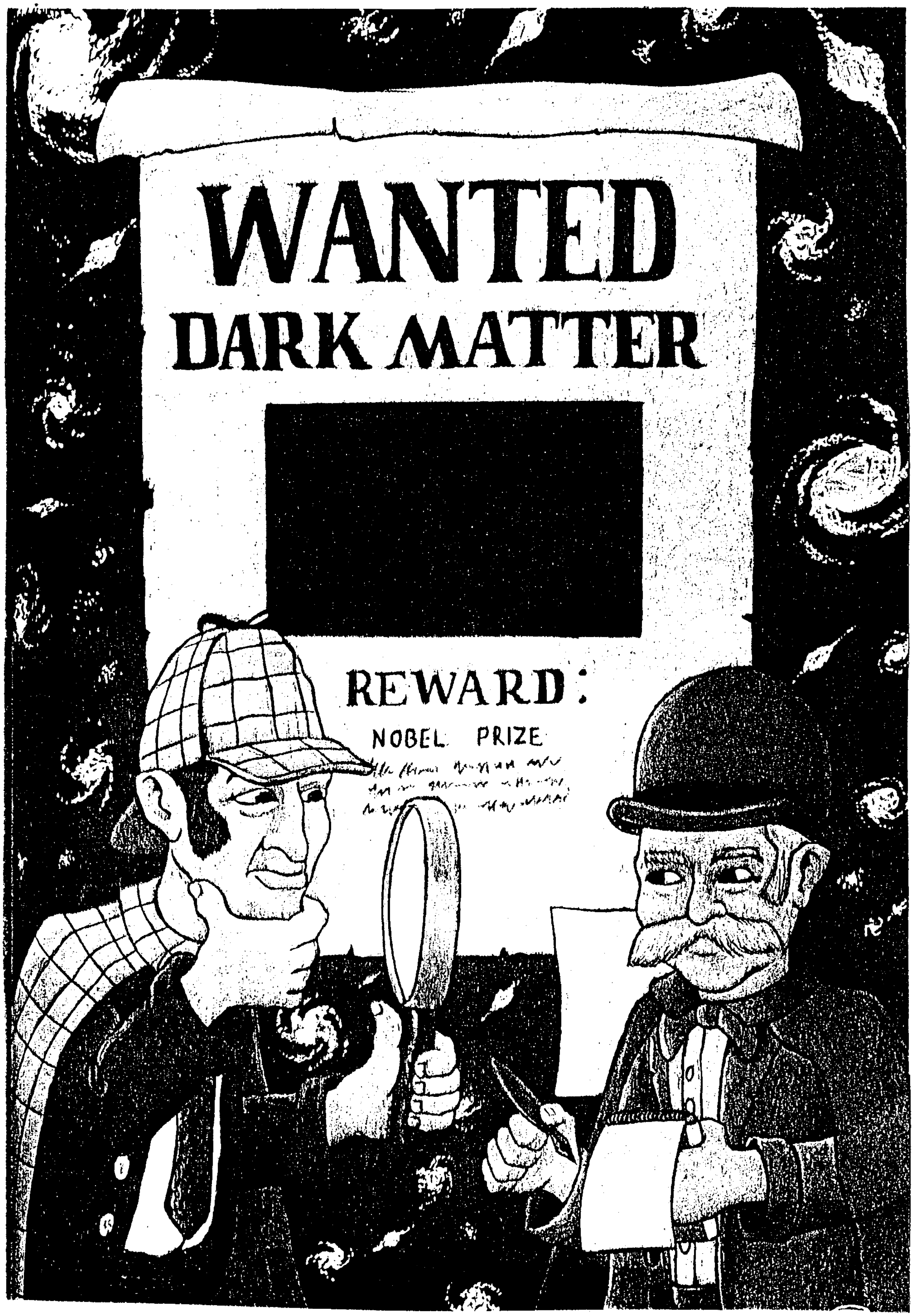
BY JOEL R. PRIMACK

"When you have eliminated the impossible, whatever remains, however improbable, must be the truth," said the great fictional detective Sherlock Holmes.

Mounting evidence has led astronomers to just such an improbable conclusion: At least 90 per cent and possibly 99 per cent of all the matter in the universe is completely invisible. Astronomers call this invisible stuff *dark matter*, and as a result of its discovery, they are faced with two of the biggest mysteries in modern science: What is dark matter, and how much of it exists?

It may be that dark matter is unlike anything we know of—or can even imagine—and will require a completely new understanding of what makes up our universe. And learning how much dark matter exists may answer the greatest question of all—the ultimate fate of the universe. To resolve these mysteries, astronomers and other scientists have adopted many of the methods detectives use to solve a crime. We are gathering evidence, examining it, and using our powers of deduction to come up with a solution.

An astronomer first reported the invisible matter after noting some unusual behavior in visible matter. In 1933, Swiss astrophysicist Fritz Zwicky observed that galaxies in a cluster of galaxies had higher speeds than expected. He concluded that something was causing strange gravitational effects on these galaxies.


WANTED
DARK MATTER
REWARD:
NOBEL PRIZE

Galaxies are like vast islands in deep space containing billions of stars that are held together by the force of gravity. Some galaxies are part of larger systems called *clusters*, which contain many galaxies. Most galaxies, however, belong to smaller systems called *groups*. Groups and clusters in turn form even larger structures known as *superclusters*. Just as the force of gravity keeps stars together in galaxies, so the force of gravity appears to keep galaxies together in clusters.

This same force of gravity keeps planets orbiting around the sun, rather than flying off into space. How great a force gravity exerts depends on the mass of the objects attracted and the distance between them, a principle discovered in the mid-1600's by English astronomer and mathematician Sir Isaac Newton. The amount of mass and the distance between objects also determine how fast the objects travel as they orbit each other. For example, in our solar system, the sun is the most massive object, making up about 99.8 per cent of the mass of the solar system, and the force of its gravity keeps Earth and the other planets in orbit around it. The orbital speeds of the planets decline with increasing distance from the sun. The planet nearest the sun, Mercury, travels at an orbital speed of 48 kilometers (30 miles) per second, while the distant planet Pluto orbits at a speed of 4.7 kilometers (2.9 miles) per second.

Using Newton's equations, astronomers can calculate the amount of mass or matter present in the solar system—or in a galaxy or cluster of galaxies—providing they know the orbital speeds and distances of the orbiting bodies. In the cluster Zwicky observed, the galaxies were traveling at tremendous speeds relative to each other.

Astronomers are able to determine the speeds of galaxies by measuring their *red shifts*—the shift in the wavelength of light given off by the galaxies toward the longer, or red, wavelengths of the *spectrum* (the pattern of colors that make up visible light). Lines of particular colors in the spectrum, which correspond to the radiation emitted or absorbed by the atoms of different elements, are shifted toward the red end of the spectrum when the source of the light is moving away from an observer. The amount of this red shift can be measured precisely, and this amount tells astronomers just how fast the galaxies that gave off the light are traveling away from us.

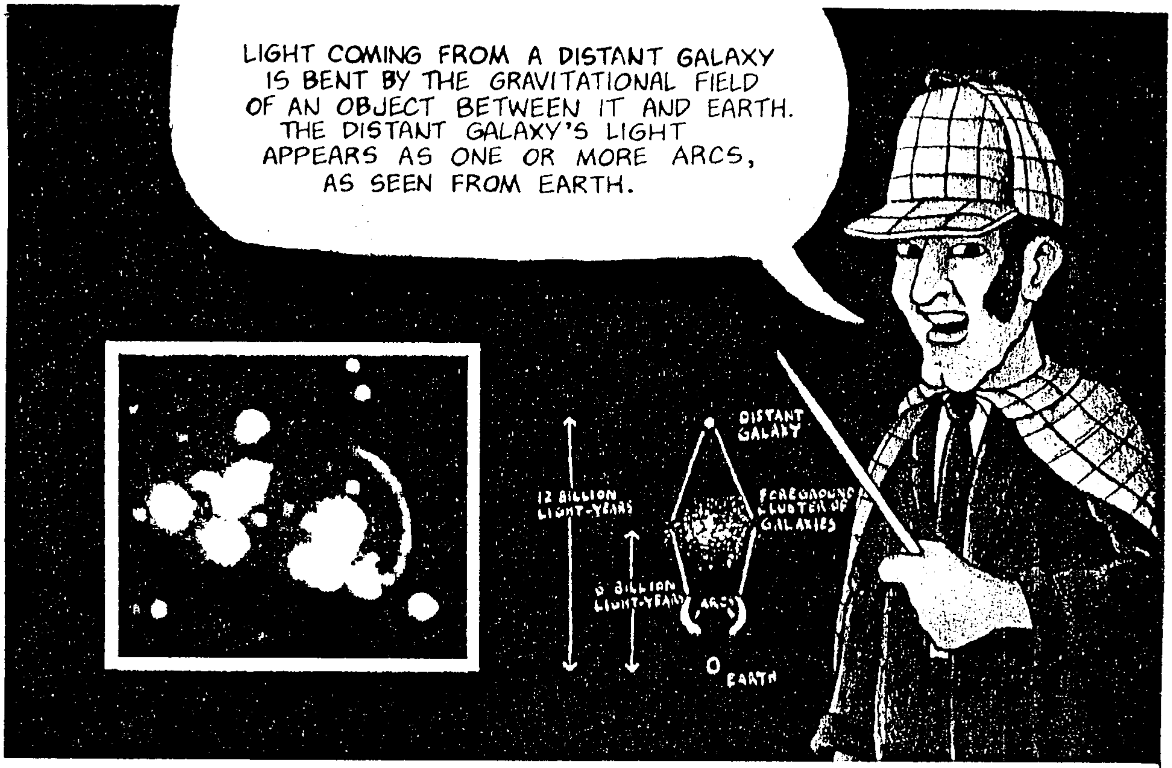
The author:
Joel R. Primack is professor of physics at the University of California at Santa Cruz.

By measuring the speeds of the galaxies in the cluster, Zwicky could calculate how much mass there was in the cluster. He determined that there was a far greater amount of matter present in the cluster than was visible through telescopes. To Zwicky, the only logical conclusion was that the predominant form of matter in the cluster could not be seen. In fact, his measurements showed that there was more than 10 times as much unseen matter as visible matter in this cluster of galaxies. In 1933, Zwicky's suggestion was considered so improbable that few astronomers accepted it.

The case of the dark matter had been opened, however, and more

Evidence for Dark Matter

Evidence that there is more matter in the universe than is visible rests on a theory of gravity, the force that keeps planets, stars, and other celestial objects in their orbits. The strength of this force depends on the mass of the orbiting objects and the distance between them. The amount of mass in the objects and their distance from each other determine the orbital speeds of the objects. Knowing orbital speeds and the distance between objects, astronomers can calculate the total mass in the orbital system.



The Evidence Mounts
A strange arc of light appears around a cluster of galaxies, photo *above*. In 1987, astronomers determined that the arc was light from a distant galaxy and that the light was bent into an arc shape by the cluster's gravitational field. From the arc's size, they calculated how much matter there must be in the galaxy cluster to cause the bending. They found the total amount of matter was much greater than what was visible and concluded that most of the matter must be invisible dark matter.

clues pointing to the existence of dark matter were found in the 1970's. These clues were uncovered after years of painstaking research by astrophysicist Vera C. Rubin and her colleagues at the Carnegie Institution of Washington in Washington, D.C. These astronomers measured the orbital speeds of stars and clouds of gas in more than 60 *spiral galaxies*. Most large galaxies, like our own Milky Way galaxy, are called spiral galaxies because they have a pinwheel shape with a bright central region and several spiral arms. The bright central region is called the *central bulge* because it is the thickest part of the galaxy, where most of the stars are located. The region of the spiral arms is known as the *disk* because it is relatively thin and flat like a phonograph disk.

Rubin found that stars and gas clouds in the outlying regions of the disk rotated around the central bulge at roughly the same orbital speeds as stars in the inner regions of the disk close to the bulge. It was as if the stars and clouds were automobiles all traveling in circular tracks with their cruise controls set to the same speed. Their orbital speeds did not decline with distance from the central bulge the way the orbital speeds of the planets decline with distance from our sun. This finding indicated that there was more matter in the outlying regions of the disk than there was near the bulge. Optical telescopes, however, clearly revealed that visible matter was concentrated in the bulge. Rubin calculated that there was 3 to 5 times as much invisible or dark matter as there was visible matter in the form of stars, gas clouds, and dust.

Astronomers using radio telescopes found evidence of still more dark matter around spiral galaxies. Visible light is only part of the range of radiant energies known as the *electromagnetic spectrum*, which also includes the long wavelength energies of radio waves. Thin clouds of hydrogen gas extending from the outermost regions of a galaxy disk cannot be seen from Earth with optical telescopes but can be detected with radio telescopes. Radio astronomers measured the orbital speeds of these outer clouds and discovered that they, too, were orbiting at the same speed as stars in the disk, confirming that there was a great deal of mass in the outermost regions. This increase in mass obviously could not come from the clouds of hydrogen gas because they are so tenuous, contributing a negligible amount of mass. So the greater amount of mass must be in the form of dark matter.

The astronomer-detectives came to another logical—though improbable—conclusion: All spiral galaxies are surrounded by huge, roughly spherical halos of dark matter that cover vast regions of space. Most astronomers now think that these halos of dark matter explain why gas clouds in the outermost regions of galaxies orbit at the same speed as stars in the inner disk. No one can be certain, but some astronomers estimate that the halo around the Milky Way, for example, may extend as far as 500,000 *light-years* from the central bulge. (One light-year is the distance that a beam of light travels in one year, about 9.5 trillion kilometers [5.9 trillion miles].) By contrast, the radius of the visible matter in the Milky Way is only about 50,000 light-years.

Like all good detectives, astronomers require more than circumstantial evidence—even if the few clues are solid—to reach a firm conclusion. For more than 50 years after 1933, the evidence for dark matter around clusters of galaxies consisted solely of measurements of the speeds of the galaxies. Then another clue was discovered in January 1987, by astronomers Roger Lynds of the Kitt Peak National Observatory in Tucson, Ariz., and Vahé Petrosian of Stanford University in California.

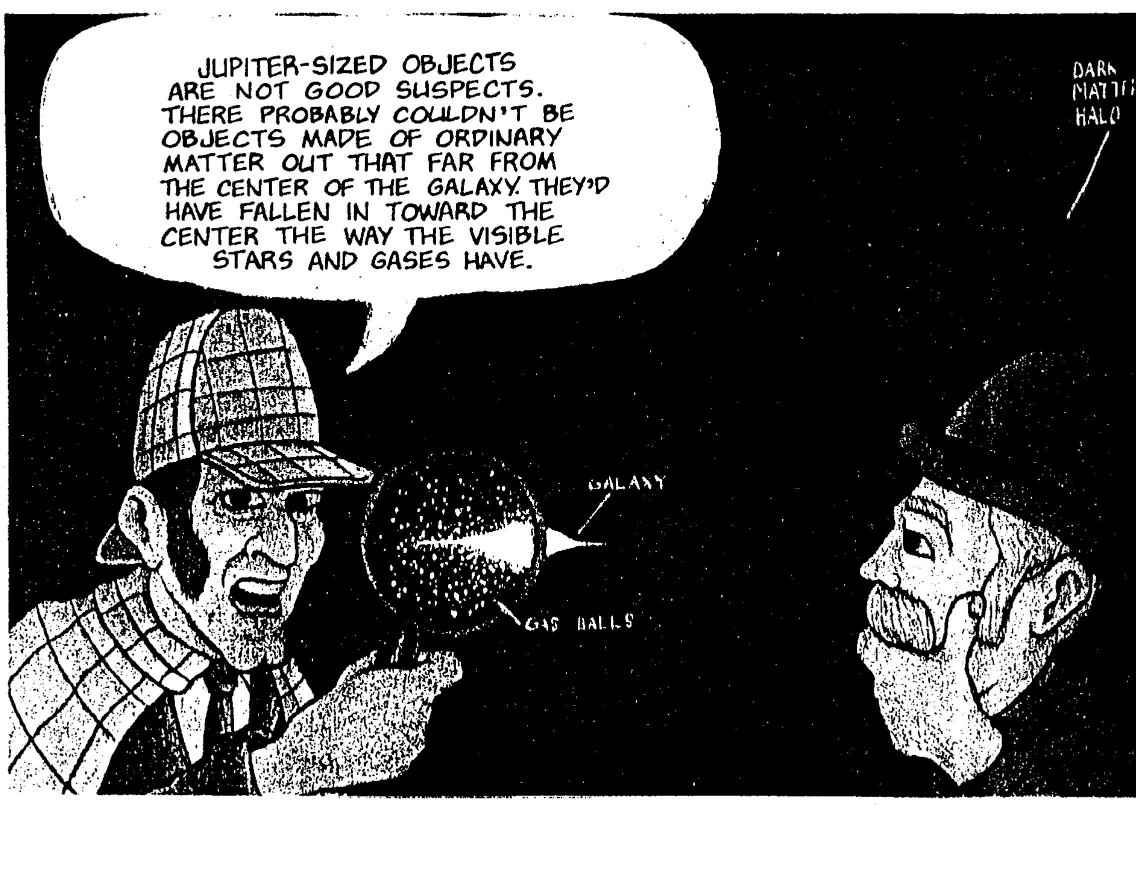
Lynds and Petrosian discovered faint arcs of light around the centers of two galaxy clusters. The French astronomer Genevieve Soucail and her colleagues measured the red shift of the light from one of the arcs and found that the light came from a distant galaxy, about twice as far away from Earth as the cluster, which is known as Abell 370. Physicist Albert Einstein had predicted in 1936 that such arcs could occur due to gravitational bending of light. The arc is an optical illusion, like a mirage, caused when the light from the distant galaxy is bent as it passes near the gravitational field of the galaxy cluster. This bending of light from a distant object by the gravity of a foreground object is called a *gravitational lens*. In effect, a gravitational lens is the greatest telescope in the universe, collecting and focusing the light of distant galaxies that otherwise would be much too faint for us to see. From the size of the arc, astronomers can deduce the amount of mass in the cluster causing the gravitational bending of light. In the case of Abell 370, scientists calculated that the total mass in this cluster was about 60 times greater than the cluster's visible mass. This discovery independently confirmed the existence of dark matter around a galaxy cluster. Zwicky's conclusion—seemingly improbable in 1933—had become an accepted theory by the 1980's.

But what is dark matter made of? No one knows for certain. One possibility is that dark matter is made of atoms, the building blocks of the ordinary matter that we see and touch in everyday life. Many astronomers, however, suspect that the dark matter is not made of atoms at all, but rather is some exotic unknown form of matter.

Ordinary matter either gives off radiation in the form of light, as stars do; or reflects it, as planets do; or absorbs it, as dust does. If dark matter is made of ordinary matter that gives off radiation in some form, it should have been detected with telescopes and instruments that are sensitive to visible light, infrared rays, radio waves, X rays, or any other form of electromagnetic radiation. With such telescopes, astronomers have surveyed the universe at all wavelengths of the electromagnetic spectrum and have been unable to find any radiation in the dark matter halos. This has led some astronomers to conclude that dark matter is not ordinary matter.

Another argument that has led astronomers to conclude that dark matter is probably not ordinary matter is that the halo is so much

Suspect:
Jupiter-Sized Objects
Dark matter might be ordinary matter. Some scientists have thought, for example, that there might be objects such as balls of gas about the size and mass of the planet Jupiter and that they might be the dark matter. At very great distances, such as in the vast halo of dark matter that seems to surround spiral galaxies, these objects would be too small and too cool for our telescopes to detect.



more spread out than the visible matter in a galaxy. If the dark matter were made of ordinary matter, its distribution should be more like that of the visible parts of the galaxy.

As far as astronomers can tell, if dark matter is made of ordinary matter, it could take only two forms that would not conflict with observations already made by astronomers. One form could be balls of gas comparable in size to Jupiter and located mainly in the halos surrounding the galaxies. Although Jupiter is the largest planet in the solar system, it is small in comparison with stars. Jupiter has a diameter of 142,700 kilometers (88,700 miles), compared with the sun's diameter of 1,392,000 kilometers (865,000 miles). We can easily see Jupiter with the unaided eye because it is within our solar system and reflects light from the sun. But at the vast distances of the dark matter halo, objects the size of Jupiter would be too small and too cool to be detectable with current instruments.

The other form could be *black holes*—the collapsed cores of dead stars that have become so dense that not even light can escape their gravitational field. If enough black holes existed, they could account for the dark matter, yet could be detected only indirectly by their gravitational influence on visible objects. (Other dead stars with collapsed cores, such as white dwarfs and neutron stars, still give off enough radiation to be detected. There do not appear to be enough of these dead stars to account for the dark matter.)

Many astrophysical detectives doubt that ordinary matter suspects are responsible for the dark matter. Motive, always something a

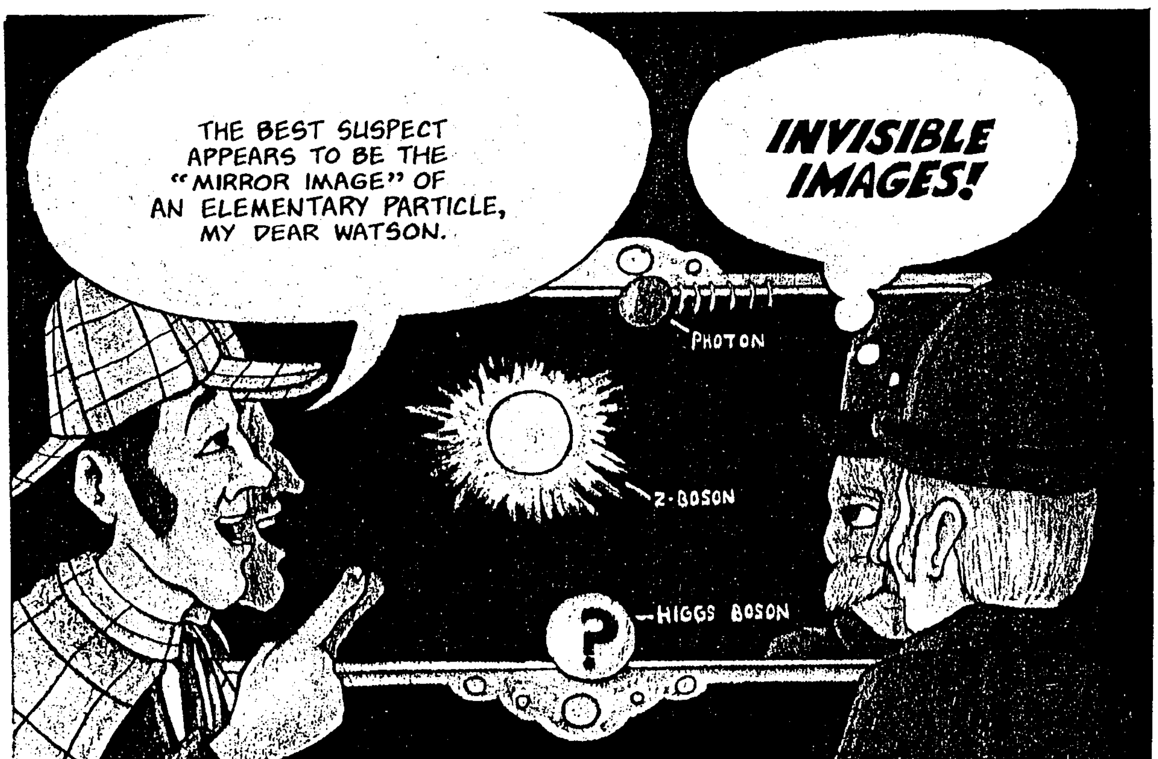
Suspect: Black Holes
Dark matter might consist of black holes, which are very strange but could still be made from ordinary matter. A black hole can form from a star that has collapsed to become so dense that not even light can escape from its gravity. Black holes are powerful enough to suck in anything that comes too close to them.

detective looks for, seems to be missing in the case of both suspects. For example, if black holes accounted for the dark matter, there would have to be about 10 billion black holes in our galaxy alone. But black holes are the remnants of extremely massive stars, and such unusually massive stars are rare today. Most stars in our galaxy have about the same mass as the sun.

Moreover, only black holes that are remnants of supermassive stars could be dark matter candidates. Astronomers and physicists have calculated that only stars several hundred times more massive than the sun could evolve into black holes without ejecting most of their mass in gigantic explosions known as *supernovae*. Stars with less mass but still about 20 times more massive than the sun would become black holes after exploding as supernovae and ejecting matter rich in heavy elements, such as carbon and silicon. But the amount of heavy elements that would have been produced in our galaxy if a great number of such explosions had occurred has not been observed. So black holes from less massive stars can be ruled out, leaving only black holes that evolved from supermassive stars as dark matter suspects. Astronomers can't think of a good reason why stars so much more massive than the sun would have formed and then collapsed to black holes in large enough numbers to account for the dark matter.

Motive is also a problem with the gas-ball suspects. Astronomers can't think of a good reason why objects much smaller than the sun, such as Jupiter-sized balls of gas, would have formed in large enough numbers to account for the dark matter. The sun, which is 1,047

Suspect: WIMP's
Dark matter may not be made of atoms, the building blocks of ordinary matter. The theory of supersymmetry says that in the early universe every elementary particle we know of had a counterpart, a "mirror image," called a *supersymmetric partner.* They would be *weakly interacting massive particles* (*WIMP*'s). The lightest supersymmetric partner of a force particle, such as the photon, the Z boson, or the hypothetical Higgs boson, might still be around today and could be the dark matter that makes up most of the universe.



times more massive than Jupiter, makes up 99.8 per cent of all the mass in our solar system. If dark matter were made up of Jupiter-sized, undetectable balls of gas, there would have to be 10,000 such objects for every star in the galaxy, which has about 100 billion stars. Yet it seems unlikely that there could be so many billions of Jupiter-sized objects in the galaxy halos without some of these objects becoming massive enough to burn nuclear fuel and become visible as stars. For example, an object just 80 times more massive than Jupiter would have temperatures hot enough to ignite nuclear reactions.

Motive, however, is the trickiest part of any detective work. Although no one can think of a reason why such gas balls should have formed, one day someone may find a reason. The motive may be there; we just haven't discovered it yet.

One important reason why many astronomers think the dark matter is not made of atoms is based on the observed amounts of elements in the universe and on a theory of *cosmology* (the study of the origin and history of the universe). This theory, known as the *inflationary theory*, predicts a certain value for the average density of matter in the universe called the *critical density*.

Using the spectral lines that are given off by the atoms of different elements, astronomers have surveyed the universe with their telescopes and have calculated the relative amounts of the elements that make up visible matter. These studies have shown that about 75 per cent of the visible matter in the universe consists of ordinary hydrogen atoms. Helium atoms form about 25 per cent of the visible matter, and all the elements heavier than helium make up less than 1 per cent of the visible matter in the universe. Deuterium, a heavy form of hydrogen, accounts for only about a thousandth of 1 per cent of the visible matter. Although only a tiny percentage of visible matter, the amount of observed deuterium is important because it indicates the density of matter in the early universe.

The observed amounts of elements agree with the *big bang nucleosynthesis* theory developed by nuclear physicists. This theory describes how the lightest atomic elements would have been *synthesized* (formed) soon after the *big bang*, the explosive event that scientists think created the universe. According to this theory, the temperature in the early universe was so high that the universe was a giant nuclear fusion reactor, creating deuterium, helium, and other nuclei from neutrons and protons. The relative amounts of the different kinds of nuclei were determined by the density of matter in the early universe. Deuterium is a sensitive indicator of the density of matter in the early universe. The more ordinary matter there is, the less deuterium is produced. Moreover, deuterium cannot be created in stars but can only be destroyed in stars. As a result, there could not have been any less deuterium in the early universe than the amount observed today. Knowing the amount of deuterium, scientists can calculate an upper limit on the density of ordinary matter in the early universe.

The calculations indicate that the total density of ordinary matter in the universe is not greater than about 14 per cent of the critical density predicted by the inflationary theory. So if ordinary matter cannot exceed 14 per cent of critical density, then the remaining matter—at least 86 per cent of the total matter in the universe—must be made of something other than atoms.

What could this other exotic matter be? Detectives working in the field of *particle physics* (the study of elementary particles) have theorized about the existence of particles they call *w*eakly *i*nteracting *m*assive *p*articles (WIMP's) that could be the dark matter. Physicists came to propose the existence of unknown new particles, including WIMP's, as they studied an entirely different problem—the search for a master force in the universe. Particle physicists divide the fundamental elementary particles into two types: *fermions* and *bosons*. Fermions include all the particles that make up matter, such as the protons and neutrons that make up the atom's nucleus and the electrons that whirl about the nucleus. Subatomic particles called *quarks*, which are the basic building blocks of protons and neutrons, are also considered fermions.

Bosons are particles that transmit forces between fermions. All the forces that hold together the fermions in an atom are due to the emission and absorption of bosons. For example, the electron is bound to the nucleus by the electromagnetic force, one of the four fundamental forces in nature. The boson that transmits this force is called a photon. The exchange of photons between the electron and the nucleus is what keeps the electron bound to the nucleus.

In addition to the electromagnetic force, physicists have identified three other fundamental forces that govern the universe: the *strong force*, the *weak force*, and gravity. The strong force holds quarks together to form protons and neutrons, and this force is transmitted by a boson called the *gluon*. The weak force, which is responsible for certain forms of radioactivity, is due to the exchange of bosons called *W* and *Z* particles. Gravity is due to the exchange of hypothetical bosons called *gravitons*. All of these bosons and fermions, except the graviton, are known to exist because they have been detected in experiments.

The problem that particle physicists were trying to solve when they speculated on the existence of new particles was whether in the earliest moments of the universe's creation, the four fundamental forces were part of a single, unified force. An idea that seems to be vital to any theory that unifies all the forces is called *supersymmetry*. Supersymmetry predicts that for every kind of boson there is a corresponding kind of fermion, and for every kind of fermion there is a corresponding kind of boson. For example, the photon would have a fermion partner called a *photino*. The electron would have a boson partner called a *selectron*, and each kind of quark would have a boson partner called a *squark*. In other words, every force or matter particle now known to exist would have a hypothetical partner, and physicists call these *supersymmetric partner* particles. Supersymmetry can be tested in laboratory experiments that attempt to create supersymmetric partner particles using particle accelerators. Physicists currently are working on such experiments at all the large particle accelerators in the world.

Most of these supersymmetric partners would have been unstable and would have gone out of existence long ago in the early universe. But, according to the theory, the lightest supersymmetric partner particle would be stable and would still be in existence today, an exotic relic of the big bang that could be the dark matter—as physicist Heinz R. Pagels and I pointed out in 1982. Supersymmetric theories indicate that this particle would have a mass several times greater than a proton and yet would interact weakly with other particles. It would be a weakly interacting massive particle, or WIMP.

WIMP's would be very hard to detect because of their weak interactions with ordinary matter. In fact, many of the WIMP's that form the dark matter in our galaxy could be going through your body as you read this without your being aware of it. Once in a great while, however, one of these WIMP's would strike the nucleus of an atom of ordinary matter. Physicists have shown that several kinds of very sensitive detectors could be built in underground laboratories to detect this kind of event. For example, if a crystal of a substance such as pure silicon were cooled to a very low temperature, just a thousandth of one degree above *absolute zero* (−273.15°C [−459.67°F.]), the collision of just one dark matter WIMP with the nucleus of a silicon atom could raise the temperature of the crystal enough to be measured. In 1989, experimental physicists in the United States and several European countries began building WIMP detectors to test these theories.

Other physicists were building detectors to trap another dark matter suspect, the *axion*, a hypothetical particle. The existence of axions, like supersymmetric WIMP's, was predicted by theories of elementary particle physics that had nothing to do with astronomy. Only later did axions become dark matter suspects. Axions would be like WIMP's in that they, too, would interact very weakly with ordinary matter. Axions, however, would be much less massive than WIMP's. In a strong magnetic field, an axion would be transformed into a photon. The experiments now being designed to determine if axions exist would detect this transformation.

The line-up of suspect particles has also included the *neutrino*. Unlike WIMP's and axions, the neutrino is known to exist. There are three types of neutrinos produced when atomic nuclei or subatomic particles disintegrate. Since 1980, scientists have conducted experiments to determine if these neutrinos have mass, but the results have


An Open or Shut Case
Astonomers want to know for sure whether dark matter exists so they can calculate how much matter there is in the universe. The total amount of matter will determine the ultimate fate of the universe, which right now is expanding rapidly in all directions like an enormous balloon.
IF THERE IS NOT ENOUGH MATTER, THE UNIVERSE WILL CONTINUE TO EXPAND FOREVER UNTIL ALL THE STARS BURN OUT. THIS ICY ENDING WOULD BE THE BIG CHILL.
BIG CHILL
IF THERE IS TOO MUCH MATTER, THE UNIVERSE'S EXPANSION WILL EVENTUALLY HALT DUE TO THE FORCE OF GRAVITY, AND THE UNIVERSE WILL BEGIN TO SHRINK UNTIL IT COLLAPSES IN WHAT IS CALLED THE BIG CRUNCH.
BIG CRUNCH

been inconclusive. If any of these neutrinos has a mass about one-hundredth of 1 per cent of the mass of the electron, it could be the dark matter particle.

Many astronomers doubt, however, that any neutrino could be the dark matter. Neutrino dark matter, also called *hot* dark matter, would have led to what astronomers call *top-down galaxy formation*. According to the top-down theory, superclusters of gas and neutrinos would have formed first, then later broken down into galaxies. But much observational evidence appears to rule out this theory. For example, astronomers have determined that galaxies are old, but superclusters are young.

For this and other reasons, many astronomers think the dark matter must be what they call *cold* dark matter. WIMP's and axions are cold dark matter particles. Cold dark matter would lead to what astronomers call *bottom-up galaxy formation*. This theory maintains that galaxies formed first and later came together to form clusters and superclusters.

Many astrophysicists in the 1980's used computers to simulate galaxy formation with either cold or hot dark matter particles. The computer models that used cold dark matter produced a picture of how galaxies are distributed that is remarkably similar to what astronomers actually observe. The hot dark matter models, however, produced clumps of galaxies unlike anything observed.

There are deeper aspects to the dark matter case than just pinning down the right suspect. Finding out what the dark matter is will help answer one of the most important questions in astronomy: Will the universe continue to expand? We know that the universe is expanding because when astronomers observe all but the nearest galaxies, the light from those galaxies is red-shifted, indicating that they are moving away from us. In fact, galaxies are speeding away from each other in all directions due to the expansion of space itself. Whether the universe will continue to expand forever or whether the expansion will slow and ultimately reverse itself depends on how much matter there is in the universe.

If there is little matter, the expansion will go on forever long after all stars in the universe have burned out in an icy end. But if there is a lot of matter, the expansion will halt due to the force of gravity, and the universe will eventually contract to infinite density—the *big crunch*. A third possibility is that there may be just enough matter in the universe to achieve critical density. In this case, the expansion will continue but at an ever slowing rate.

Uncovering the composition of dark matter will help astronomers determine whether there is enough matter—both visible and invisible—to reach the critical density. But for now, the case is still open.

For further reading:

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