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DARK MATTER

MOST OF THE MATTER IN THE UNIVERSE IS NEITHER BOUND UP IN STARS OR PLANETS NOR DISPERSED IN CLOUDS OF "ORDINARY" PARTICLES. EXPERIMENTERS ARE RACING TO ANSWER THE QUESTION, WHAT IS IT MADE OF?

By DONALD GOLDSMITH

Every second of every day, millions of dark-matter particles may course through every cubic inch of your body. The particles may be WIMPs, or they may be axions. They may be higgsinos, majorons, neutralinos, photinos, pyrgons, quark nuggets, skewons, wimpzillas, or zinos. If you choose, you can ignore these whimsically named creatures of the cosmos, just as they ignore you: they steadfastly refuse to interact with any of the particles that form you. Then again, maybe these strange particles don't exist at all.

Astronomers readily admit that they don't know what dark matter is—just that it dominates the universe. You might conclude that this predicament has plunged astronomers into a pit of professional confusion, from which they are trying to escape by creating a virtual cosmos out of hypothetical matter. And you'd be partly right. But astronomers have also gained remarkably firm knowledge of dark matter, hard as that seems to square with the continuing obscurity of its identity.

First and foremost, dark matter—matter that emits neither light nor any other detectable form of radiation—is real, notwithstanding the struggles of a small minority of physicists to explain it away. It was created immediately after the big bang, 14 billion years ago, and has persisted ever since, forming the bulk of all the matter in the cosmos. In spite of its mysteries, dark matter is detectable through a web of observations that complement and support one another. In fact, American and European physicists are racing to catch its invisible particles in new, ever improving detectors. What excites them is the sense that they are closing in on the answer to one of the great cosmic riddles: What is most of the universe made of?

What makes astronomers so sure that dark matter exists? The answer is gravity. All matter, including invisible matter, exerts gravitational forces on the matter we can see.

Fritz Zwicky, the prickly Bulgarian-Swiss-American astronomer who was the first to conclude that dark matter must exist, introduced the concept in 1933. By applying Newton's laws and measuring the speeds of individual galaxies within a cluster of galaxies, Zwicky could deduce the mass of the cluster. He also determined the amount of visible matter in the clusters by measuring the brightness of the galaxies that form them. Those two measurements showed that a typical giant cluster of galaxies comprises at least ten times more invisible matter than what is visible. Later observations would rule out the possibility that the invisible matter is all made up of diffuse gas floating among the galaxies. Such intergalactic gas does exist, but in nothing remotely like the quantities needed to account for most of the dark matter.

Zwicky's conclusions gained scant attention from his colleagues. The snub was partly provoked by his cantankerous nature—he referred to fellow astronomers as "spherical bastards," meaning that they were bastards no matter how you looked at them. But a greater hurdle was the revolutionary implication of his idea: few could accept that most of the universe remained to be discovered.

So dark matter suffered three decades of neglect. Then in the 1970s two astronomers at the Carnegie Institution of Washington (D.C.), Vera S. Rubin and W. Kent Ford Jr., mapped the motions of stars within galaxies close to our own Milky Way. They reached essentially the same conclusion as Zwicky had: each galaxy includes enormous amounts of dark matter, far more than all the luminous stuff in the galaxy's stars. The bulk of it forms a giant, dark halo extending far beyond the star-strewn galactic expanses that we see.

Astronomers today, applying Zwicky's logic, are still detecting vast quantities of dark matter in distant galaxy clusters. Among the clusters, they have observed clouds of hot gas, which would have escaped the clusters' gravitational pull billions of years ago if the clusters had no more mass than that of their stars.

Impressive as those observations are, there's even more evidence for the unseen presence of dark matter: the phenomenon of "gravitational lensing." Because gravity bends space itself (Einstein's finest insight into nature), light passing close by a massive object deviates from a straight-line trajectory. Hence if a massive object happens to lie almost directly along our line of sight to a more distant source of light, such as a galaxy, the light we see will be bent or even focused, much as if the intermediate object were an optical lens [*see illustration on opposite page*]. A small amount of light bending, or "lensing," can distort the galaxy into an unusual shape, just as the thick glass bottom of an old Coke bottle distorts the shape of a light bulb when you look at the bulb through the bottle. Stronger lensing can actually create multiple images of the same light source. Gravitational lensing enables astronomers to map the distribution of all matter, not just visible matter, because all matter can give rise to a lensing effect.

Map of dark matter (light blue), digitally superposed on a photograph made by the Hubble Space Telescope, shows that a giant ring of invisible mass surrounds the dense core of a giant cluster of galaxies called ZwC10024+1652, about 5 billion light-years from Earth. Astronomers mapped the distribution of mass in the galaxy cluster by observing the effects of gravitational lensing on background galaxies.

What, then, is this dark matter that makes up by far the bulk of all the matter in the universe? No one knows. But cosmologists do know one thing for sure: most of it cannot be anything like the matter familiar to us.

Cosmologists classify all matter into two kinds: baryonic and nonbaryonic, or, basically, the ordinary and the exotic. "Baryon" comes from the Greek root *barys,* meaning "heavy"; the term was coined to refer to the heavy particles that fuse together in the nuclei of ordinary atoms—neutrons and protons. They far outweigh the electrons, which are leptons, or "light" particles, not baryons. With the realization that matter exists in more exotic forms, the term "nonbaryonic" came to denote not only leptons but also all other particles that do not participate in nuclear fusion. One of the most important clues to the mystery of dark matter comes from the growing evidence that the bulk of it—and thus, most of the matter in the universe—is nonbaryonic matter.

Baryonic matter forms stars, planets, moons, and even the interstellar gas and dust from which new stars are born. Nonbaryonic matter includes neutrinos, tiny particles each having less than a millionth the mass of the already diminutive electron. Neutrinos were once regarded as likely candidates for dark matter because they exist in such prodigious numbers, but they have now been excluded from the dark-matter sweepstakes. Detailed studies of how galaxies form suggest that dark matter is most likely made of particles whose masses range from roughly that of the proton to several hundred times as much.

How do astrophysicists infer that such hypothetical particles of dark matter must be nonbaryonic? They can estimate the total amount of matter from the effects of gravitational lensing and the distribution of cosmic background radiation. The baryonic part of that total then comes from the current understanding of how the cosmos behaved during its earliest epochs. The big bang, with which the universe began, opened an era of nuclear-fusing fury, a time when all particles crowded together at unimaginably high densities and temperatures. All creation then resembled the cauldron at the core of a star, only far more so. From the countless nuclear fusions that took place in those first few minutes after the big bang, there emerged the basic ratio of nuclei in the universe today: almost entirely hydrogen and helium, with only a minute smattering of all heavier nuclear varieties.

By the end of its first few minutes, the universe had expanded and cooled, dipping below the billion-degree temperatures needed for nuclear fusion. Only in much later, highly localized events did the stars cook up almost all the heavier elements, such as the carbon, nitrogen, oxygen, silicon, and iron that make up our planet and ourselves. Those heavier nuclei, however, comprise no more than 2 percent of the mass of all baryonic matter. The other 98 percent is still made up of hydrogen, helium, and their isotopes, created immediately after the big bang. By measuring the relative amounts of the various isotopes of hydrogen and helium nuclei, cosmologists can deduce how much baryonic matter took part in the great crucible of cosmic nuclear fusion in the first half hour of the universe.

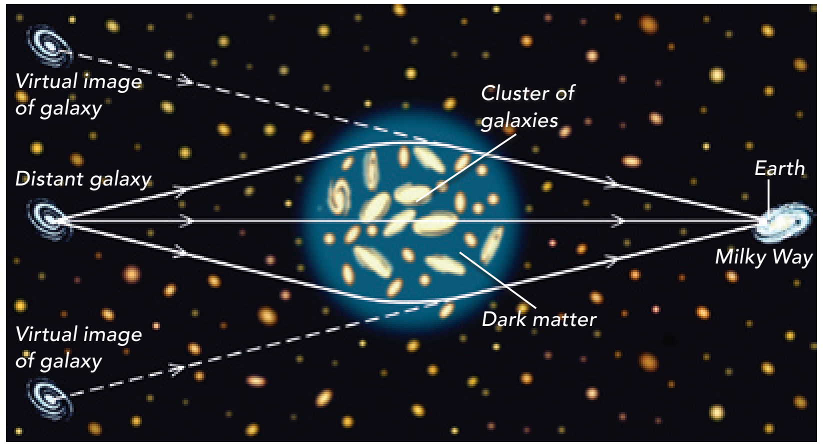
Those results, now confirmed by detailed studies of the cosmic background radiation, lead to a startling conclusion. Baryonic matter—some of it in stars, but much more in diffuse interstellar gas—forms no more than a sixth of all matter in the universe. The other five-sixths must be nonbaryonic matter, either in the form of elementary particles or clumped into much larger objects.

The fascination with the unruly properties of dark matter—its distribution in space, and most of all its predominantly nonbaryonic nature—has given rise to a flourishing dark-matter community. Some members can point to achievements such as improved maps of dark matter and its distribution in intergalactic space [*see illustration on the following two pages*]. Others strive to design, build, and operate experiments that may someday determine the nature of nonbaryonic dark matter, or at least eliminate from contention some of the hypothetical particles that elementary-particle physicists have proposed.

Before surveying those experiments and the hypotheses that motivate them, it's worth noting that a few ingenious minds will have none of the dark-matter mystery. Instead, they suggest, the observations show merely that physicists don't yet fully understand gravity. Suppose that at the greatest cosmic distances, gravitational forces deviate slightly from what Newton proposed and Einstein refined. In that case, the motions of stars and galaxies might not reflect the existence of enormous quantities of dark matter, but rather the simple refusal of the universe to obey what physicists presume to be the laws of nature.

The Israeli physicist Mordehai Milgrom of the Weizmann Institute in Rehovot, Israel, proposed that approach, and for a time his idea seemed to explain the observational results without recourse to much dark matter. But to many astronomers now, Milgrom's idea seems on the verge of being disproved. Increasingly accurate observations of stellar and galactic motions at various distance scales seem to confirm existing theories of gravity.

If Einstein's theory of gravity is correct, as appears to be the case, then nonbaryonic matter—matter forever different from all known matter—has always ruled the universe. And the best hope for discovering just what form it takes now rests on finding some of it—at least a tiny amount!—here on Earth. But that poses a dilemma. The basic nature of nonbaryonic dark matter, its extreme unwillingness to engage in any interactions with ordinary particles, makes it extremely difficult to detect.



Gravitational lensing can occur when light from a distant galaxy, center left, passes through a dark-matter halo around a cluster of galaxies. Here the gravitational pull of the dark matter deflects the light in such a way that an observer on Earth sees two additional images of the galaxy. The diagram is highly idealized; the distances and angles are not drawn to scale.

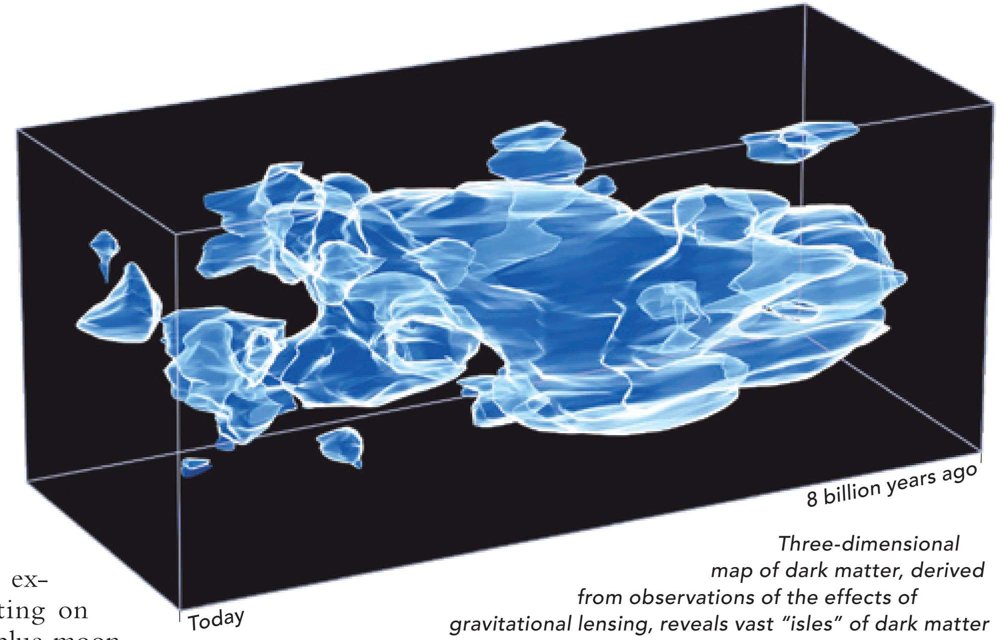
The dark-matter community, fully aware of the difficulties, has concentrated on experiments designed to find the leading dark-matter candidates. The candidates come in two categories: relatively large objects, and submicroscopic elementary particles, which would have to exist in huge quantities. The sizable dark-matter candidates have the generic name MACHOs, short for "massive compact halo objects." MACHOs might be black holes with masses something like that of a star; or smaller, more numerous black holes with masses similar to those of planets; or perhaps the cores of burned-out stars that collapsed but did not form black holes. Gravitational lensing can reveal MACHOs, and astronomers have even found a few with starlike masses. But the results so far imply that MACHOs cannot supply the bulk of the cosmic mass.

If so, the best hopes lie with nonbaryonic elementary particles, which exist so far only in theory. But some of the theories predicting their existence display promising elegance and symmetry, so particles are the favored dark-matter candidates. Two kinds of hypothetical particles seem the most appealing.

First is the axion, a particle named after a laundry detergent, because its hypothetical properties cleaned up a conflict between a theory known as quantum chromodynamics and certain experimental results. Each axion would have an exceedingly small mass—less than a millionth of the electron's own tiny mass.

If axions do exist and throng our galaxy, they must occasionally be scattered by the magnetic fields that permeate the Milky Way. The scatterings would generate radio waves at a frequency that depends on the small (and unknown) mass of the axion. The world's most advanced axion detector, at the Lawrence Livermore National Laboratory in California, seeks those radio waves by searching a wide band of possible frequencies with supremely sensitive amplifiers. So far, all axion searches have proven fruitless, but the search goes on.

If not axions, why not WIMPs? The name stands for "weakly interacting massive particle"—a concise description of the second leading candidate among hypothetical dark-matter particles. "Weakly interacting" means interacting mainly via the weak force, the force responsible for certain kinds of atomic "decay" and the least familiar of the four fundamental forces in nature. "Massive" in this context means "at least a few dozen times the mass of a proton." (The name "MACHOs," for dark-matter black holes, was chosen to contrast with "WIMPs," which was proposed first.) Because WIMPs arise from the predictions within a class of persuasive theories of elementary particles called supersymmetric, many particle theorists think WIMPs exist.



Three-dimensional map of dark matter, derived from observations of the effects of gravitational lensing, reveals vast "isles" of dark matter that dominate the large-scale structure of the universe. The map covers a patch of sky 1.6 degrees on a side, out to 8 billion light-years from Earth. The ancient light from distant galaxies enables astronomers to reconstruct how dark matter has evolved (right to left) since early in the history of the universe.

To find the elusive WIMPs, experimental physicists are betting on the likelihood that, once in a blue moon, a WIMP will collide with ordinary matter. Such a collision would lead to a wimpy—as in "amazingly small"—effect in the bowels of a WIMP detector, so extraordinary measures must be taken if physicists hope to notice it. Experimenters reduce the normal atomic vibrations of the sensors within the detector as far as possible by cooling the sensors close to absolute zero. Placing the apparatus deep underground shields it from interference from less penetrating potential sources of spurious signals, such as the cosmic rays that continuously bombard the Earth.

Attempts to find the elusive particles that form dark matter have so far yielded only **hope** and **construction contracts.**

At least half a dozen competing teams of experimenters from Europe and the United States are now operating and improving their WIMP detectors, which build on two basic designs. In the first design, the sensors are several dozen crystals, each weighing about a kilogram, made of highly purified germanium or silicon. Two detectors employ that design, one inside the Gran Sasso tunnel, nearly a mile beneath Italy's Apennine mountains, and the other at the bottom of a decommissioned mine in northern Minnesota. If a WIMP strikes an atom in one of the crystals, the crystal should ever so slightly heat up and vibrate. So far the crystal detectors have found no WIMPs, but the crystals may well fail to provide a sufficiently large target to succeed in only a year or two of operation.

To increase their chances of registering WIMP impacts, the experimenters naturally would like to enlarge the target, but with crystal-based detectors, that poses technological difficulties. Enter the second, and newer, kind of WIMP detector, whose target is a pool of ultra-pure, liquefied inert gas. Ongoing experiments with liquefied argon or xenon detectors now operate within the Boulby mine in Yorkshire, England, and in the Gran Sasso tunnel.

Like the crystal detectors, the inert-gas detectors have yet to register a single WIMP. Nevertheless, experimenters have high hopes for success with the design, because they can scale up inert-gas detectors with relative ease. The next generation will deploy not a few kilograms but a few hundred kilograms of target material. Elena Aprile, a physicist at Columbia University who leads the attempt to find a xenon-bumping WIMP in the Gran Sasso tunnel, hopes for a sizable gain in sensitivity by the end of 2008.

In short, attempts to find the elusive particles of dark matter have so far yielded only hope and construction contracts. In more scientific language, the experimentally established upper limits on the tendency of WIMPs or axions to interact with ordinary matter have grown progressively smaller. So far those upper limits do not rule out the viability of either of these dark-matter candidates. No one can say, just yet, that axions or WIMPs do not exist in sufficient numbers, and with enough mass per particle, to account for the bulk of the nonbaryonic dark matter.

Experimenters working with both kinds of dark-matter detectors know that a formidable competitor looms on the horizon. The Large Hadron Collider (LHC), built at CERN, the European Organization for Nuclear Research, just outside Geneva, is now scheduled to begin serious operation in mid-2008. Once up and running, the LHC will be the world's biggest particle accelerator. Dug several hundred feet under the Swiss and French countryside, it will accelerate two clumps, or "beams," of particles many times around a ring more than five miles across, before smashing the two beams into each other.

Although the LHC was not designed to search for dark matter, its collisions will give birth to the most massive particles ever generated in any machine. If the LHC can verify supersymmetric particle theories, as expected, it will confirm WIMPs as real. Naturally, the builders of dark-matter detectors, currently stymied in their searches for axions and WIMPs, would like nothing better than to find the dark matter before the LHC can make its roundabout confirmation-by-implication.

They must hurry. Bernard Sadoulet, a physicist at the University of California, Berkeley, who has become the grand old man of dark-matter detection, thinks physics has a "decent chance" of ruling axions and WIMPs in or out of contention in the next five years.

And what if more sensitive experiments show that neither axions nor WIMPs can explain the dark matter? Life will go on, and so will the universe, most of it made of dark matter of unknown form, just as it is today. Inventive theorists will suggest new possibilities, and experimentally minded particle physicists will improve their detectors and their analyses. And both theorists and experimenters will continue to work in the hope that they will be the fortunate ones to resolve this fundamental cosmic mystery. Two hundred fifty years ago, the town of Whitby, in Yorkshire, produced James Cook, arguably the greatest explorer of Earth. Perhaps in the next five years the dark-matter experimenters in the Boulby mine, near Whitby, will be able to announce one of the greatest discoveries about the cosmos: the nature of dark matter. □

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