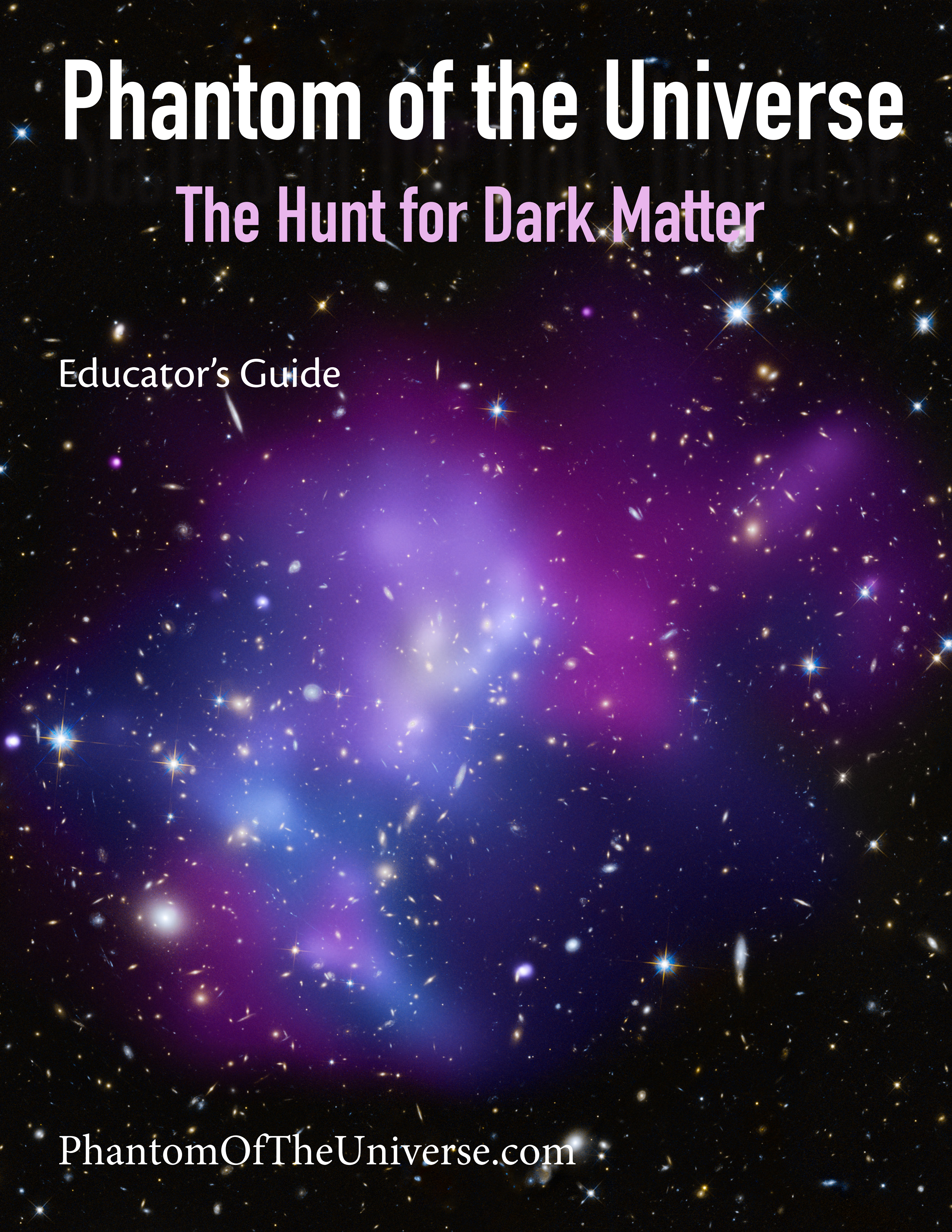
Phantom of the Universe

The Hunt for Dark Matter

Educator's Guide



PhantomOfTheUniverse.com

Big Questions About Discovery

What does it mean to discover?

Discovery can mean different things to different people and doesn't just mean traveling to unknown places or finding new things. In astronomy and physics, it is about understanding different objects and processes in our universe through the use of tools and measurement. For a world traveler, it's about rediscovering places for themselves. For a small child, it's about finding new sights, sounds, and textures. What does it mean to you?

What have humans discovered?

A lot! We have discovered the fundamental laws that control the behavior of matter in the Universe. We have figured out what atoms are made of and how they interact together. We have also discovered a lot about things we cannot physically touch or reach. Our technology creates tools to help further our understanding of things otherwise beyond our reach. By studying light emitted by celestial objects with telescopes we have learned what other stars are made of, that galaxies are formed from stars and that the universe is filled with a strange and mysterious substance that we cannot see feel or touch. Likewise, our huge particle accelerators allow us to peer deep into the microscopic world of the extremely small.

What is left to discover?

While there aren't any new continents left to discover on Earth, there is still a lot to learn about our Universe. For example, we don't know what most of the universe is made of or why the universe accelerating in its expansion. We only very recently discovered how matter in the universe gets its mass! In order to ask questions we need to figure out what we do know and, more importantly, what we don't know. There's plenty we still have questions about.

How do we discover new things?

Engineers and scientists have built many tools that help us study objects and how the world works. In space sciences, this includes satellites, space- and ground-based telescopes and robots. In physics this includes laboratory experiments like sensitive detectors and huge particle colliders. We also have conceptual tools like mathematics, models and simulations. However, one of the biggest and best tools we have is us. We work together on all of these problems, come up with the ideas and help inspire each other to not only answer questions, but to ask new questions so we can continue to discover new things.

Why is it important to discover?

Humans have an insatiable curiosity. Discovery, in any form, is about finding answers and new knowledge that helps us understand the world around us. The answers to our questions can lead to great new breakthroughs that help humans make our lives better or help us make sure we do not cause too much harm to our surroundings. Discovery and exploration also allows us to know what our place is in the universe. It is part of a long human quest to figure out how we fit in, and where we come from.

Show Overview

“Phantom of the Universe: The Hunt for Dark Matter” takes the visitor on a journey of discovery, following the efforts of scientists around the world as they try to unlock the mystery of Dark Matter. Starting with its creation during the Big Bang, the role of dark matter in the formation of galaxies and thus ourselves is explored, highlighting its discovery from its effects on the motions of stars and galaxies. The visitor is then brought back thousands of feet below the earth’s surface where teams of scientists are building extremely sensitive experiments to detect the very rare direct interactions of dark matter particles with normal matter. Finally, the visitor is taken on a whirlwind tour of the gigantic CERN laboratory where beams of protons are hurled together in head on collisions in an attempt to create new dark matter particles for study.

Background Information

What is Dark Matter?

In the 1950's the study of galaxies was an extremely exciting topic. It was only quite recently (in the early 1900's that astronomers had come to realize that galaxies were not part of our own Milky Way, but actually distant stellar "cities" of their own. An American astronomer, Fritz Zwicky, was studying the motions of galaxies within large clusters of galaxies and realized that these motions were far faster than could be explained by what he saw. The gravity of the visible galaxies was simply not enough to hold the clusters together against their tremendous velocities. There must be extra, and unseen, matter holding the clusters together. He called this Dark Matter.

While Zwicky's conclusion was mostly ignored at the time, evidence began to pile up from studies of other galaxies, the expansion of the Universe as a whole, and the distribution of the galaxies in space. By the 1980s and '90s the evidence was irrefutable: most of the matter in the Universe was dark and unseen. What's more, this Dark Matter did not seem to interact with "normal" matter except through the force of gravity.

The Big Bang

To really understand dark matter one has to go back to the very beginning, the origin of the Universe in the Big Bang. The Big Bang is simply the name we give to the state of the Universe when it was very young, very hot and very dense. It was not an explosion within the Universe, but rather it is the rapid expansion of the whole Universe at very early times.

The farther back one looks in the history of the Universe the hotter and denser it was. Since then it has been expanding and cooling off. At these late times the Universe is a frigid 2.7K, but in the first seconds the temperatures were trillions of degrees kelvin. At these temperatures new matter can be born and destroyed in a continuous cycle. Dark Matter was created at this early time and came to dominate the mass of the Universe.

Hunting for Dark Matter with Gravity

If Dark Matter is dark and hardly interacts with normal matter, then how does one detect it? Although you can't see it directly, Dark Matter does have gravity and so one can see the effects of Dark Matter. One example is the excess motion of galaxies in clusters found by Zwicky. More recently, Vera Rubin was studying spiral galaxies, flat disks whose stars all revolve around the center in the same direction. According to theory, the farther out a star is from the center the more slowly it should move, much like the slower motion of planets farther from the Sun. But Rubin measured something surprising: farther out stars move just as quickly as those close in. Again, it is as if there were extra, unseen, matter holding the stars in their orbits.

In the past couple decades another powerful, and very beautiful evidence for dark matter has emerged: The amount and distribution of galaxies in the Universe. When the Universe first formed it was extremely uniform with only tiny ripples in the distribution of matter. It is gravity that enhanced these ripples to the point where some areas of the universe are very dense (stars, planets, galaxies). But if the only matter in the Universe were what we see directly there would not have been enough gravity to have pulled together the galaxies. Without dark matter we wouldn't even exist!

Hunting for Dark Matter in the Lab

But studying Dark Matter by looking for its gravitational effects is unsatisfying. While we know it exists, and can even tell a bit about its properties, these studies will not tell us what it *is*. In the past few decades particle physicists, scientists who study the fundamental structure of matter, have begun to develop a powerful understanding of what Dark Matter *might* be. All normal matter is made up of a very limited number of types of "elementary" particles. There are electrons and "up and "down" quarks. Up and Down quarks in different combinations make up protons and neutrons. Protons and neutrons make up the nuclei of atoms. Electrons surround the nuclei to form neutral atoms. That’s it. Everything we see in the Universe is fundamentally made up of only these three particles arranged in different ways.

But what we don’t see, Dark Matter, seems to be made of a another type of particle entirely. These particles are far more massive than electrons and quarks and very hard to create. But in the very energetic collisions between particles in the early universe they were created in abundance. To study them in the lab today one has to create similarly energetic collisions. This is done in the huge particle collider called the Large Hadronic Collider (LHC). Protons are send whirling around a ring at tremendous speeds and slammed head on into protons whirling around the other way. The resulting collisions produce many particles and occasionally, it is hoped, a particle of Dark Matter. This Dark Matter particle, called a neutralino, will escape without being detected, but its signature in the shape of the collision, will remain. From the details of the dark matter production we will finally learn what Dark matter really is.

Teaching with the Show

Before the Visit

- Discuss with students some of the Big Questions at the beginning of this document. However, below are more content specific and grade appropriate questions that may be good to discuss and teach beforehand. Choose the questions that match your curriculum best or use your own questions based on major themes of the show discussed above.
- Just before the visit, encourage students to think of questions that they would like more information about and how they might want to explore those answers.
- Show them pictures of the Planetarium, Museum or Science Center where you will see the show so they are prepared for what they will be seeing and the space they will entering.
- Discuss with your students what matter is. Ask for examples and some properties of matter. Ask how we study and learn about matter. Suggest that all matter may not be the same.

After the Visit

Revisit these questions and the Big Questions after the visit and see what students learned. In order to foster students curiosity, perhaps allow them to do a project that lets them explore questions they formulated during their visit. In their project, they can ask questions, use different tools to answer what they can, and explain what future work they or other scientists can do to answer new questions. The final product could be a poster, a written proposal, a presentation to the class.

ELEMENTARY SCHOOL

- What objects are out in space or in the sky? How do they move?
- What is a star? What is a galaxy?
- What are stars/galaxies made of? Is this the only kind of matter?
- What are the properties of matter?

MIDDLE SCHOOL

- What are galaxy clusters?
- How does gravity effect the motions of stars?
- How do we find out what matter is made of?
- How is Dark Matter different from normal matter?

HIGH SCHOOL

- What was the Big Bang?
- How does gravity affect structure in the Universe?

Correlation to Standards

Elementary School

National Science Standards:

A.1 Ask a question about objects, organisms, and events in the environment

B.1 Properties of Objects and Materials

B.2 Position and motions of objects

D.2 Objects in the Sky

Middle School

National Science Standards:

A.1 Identify Questions that can be answered through scientific investigations

A.3 Use Appropriate tools and techniques to gather, analyze, and interpret data

D.1 Structure of the Earth System

D.2 Earth's History

D.3 Earth in the Solar System

MS-PS2-4. Construct and present arguments using evidence to support the claim that gravitational interactions are attractive and depend on the masses of interacting objects.

MS-ESS1-2. Develop and use a model to describe the role of gravity in the motions within galaxies and the solar system.

HIGH SCHOOL

National Science Standards:

A.1 Identify questions and concepts that guide scientific investigation

B.4 Motions and Forces

D.1 Energy in the Earth System

D.3 The origin and evolution of the Earth system

D.4 The origin and evolution of the universe

HS-ESS1-2 Construct an explanation of the Big Bang theory based on astronomical evidence of light spectra, motion of distant galaxies, and composition of matter in the universe.

HS-ESS1-4 Use mathematical or computational representations to predict the motion of orbiting objects

HS-PS2-4. Use mathematical representations of Newton's Law of Gravitation and Coulomb's Law to describe and predict the gravitational and electrostatic forces between objects.

HS-PS3-1. Create a computational model to calculate the change in the energy of one component in a system when the change in energy of the other component(s) and energy flows in and out of the system are known.

HS-PS3-2. Develop and use models to illustrate that energy at the macroscopic scale can be accounted for as either motions of particles or energy stored in fields.

Additional Resources

On the Web

Dark Matter

en.wikipedia.org/wiki/Dark_matter
This is a somewhat technical summary of the current state of this topic from Wikipedia (includes over 100 references).
http://astro.berkeley.edu/~mwhite/darkmatter/dm.html
A very short verbal explanation of Dark Matter.

astro.berkeley.edu/~mwhite/darkmatter/essay.html
An essay (without graphics) by science writer Joseph Silk. Some of the material may be out of date, since no references are more current than 1993.

csep10.phys.utk.edu/astr162/lect/cosmology/darkmatter.html
A short definition of Dark Matter (web page last modified in 2000).

math.ucr.edu/home/baez/physics/Relativity/GR/dark_matter.html
Short verbal explanation of why the Universe needs Dark Matter.

Dark Energy, Dark Matter

science.nasa.gov/astrophysics/focus-areas/what-is-dark-energy/
A good non-technical summary from NASA written for the average science-savvy reader.

How Dark Matter Works

science.howstuffworks.com/dictionary/astronomy-terms/dark-matter.htm
A surprisingly good (and sometimes entertaining) comprehensive explanation of Dark Matter written for the non-scientist (includes many graphics).

Latest in Dark Matter

http://www.scientificamerican.com/topic.cfm?id=dark-matter
List of Scientific American articles on Dark Matter.

Dark Matter Search Heats Up At Underground Lab In Ontario

http://www.huffingtonpost.com/2013/05/04/dark-matter-search-underground-lab-ontario_n_3210354.html?ir=Science

Describes a new hunt for dark matter inside a deep underground laboratory below Ontario, Canada. The project, called COUPP-60 (the Chicagoland Observatory for Underground Particle Physics), is a 30-liter chamber filled with 132 lbs (60 kg) of purified water and CF3I — an ingredient in fire extinguishers.

Search for Dark Matter: Experiment Measures Anti-matter Excess in Cosmic Ray Flux

www.sciencedaily.com/releases/2013/04/130403115313.htm

Short report from the international team running the Alpha Magnetic Spectrometer (AMS1) announcing the first results in its search for Dark Matter.

Best Map Ever Made of Universe's Oldest Light: Planck Mission Brings Universe Into Sharp Focus

www.sciencedaily.com/releases/2013/03/130321084221.htm
Short report on the Planck satellite's measurement of the Cosmic Microwave Background and the percentages of matter, Dark Matter, and Dark Energy in the Universe.

Dark Energy Alternatives to Einstein Are Running out of Room

www.sciencedaily.com/releases/2013/01/130109162034.htm
Short report on how alternatives to General Relativity and its explanations for Dark Energy are being limited by new experiments measuring the ratio of the mass of a proton to the mass of an electron.

Searching for Elusive Dark Matter Material

www.sciencedaily.com/releases/2012/11/121115141627.htm
Short report on a new experiment in South Dakota named LUX (Large Underground Xenon) to discover Dark Matter.

Gravitational Lensing

en.wikipedia.org/wiki/Gravitational_lens
A somewhat technical explanation of Gravitational lensing, including interesting graphics and animations.

astro.berkeley.edu/~jcohn/lens.html
A good summary of Gravitatinal Lensing including a list of references.

imagine.gsfc.nasa.gov/docs/features/news/grav_lens.html
A short simple summary of this topic and how it works.

Books

Dark Side of the Universe: Dark Matter, Dark Energy, and the Fate of the Cosmos
Iain Nicolson

Einstein's Telescope: The Hunt for Dark Matter and Dark Energy in the Universe
Evalyn Gates

The 4 Percent Universe: Dark Matter, Dark Energy, and the Race to Discover the Rest of Reality
Richard Panek

Dark Matter, Dark Energy, Dark Gravity
Stephen Perrenod

In Search of Dark Matter
Ken Freeman

Dark Matter, Dark Energy, Dark Gravity: Enabling a Universe that Supports Intelligent Life
Stephen Perrenod

Dark Matter and Dark Energy: A Challenge for Modern Cosmology
Sabino Matarrese (Editor), Monica Colpi (Editor), Vittorio Gorini (Editor), Ugo Moschella (Editor)

Dark Matter, Dark Energy: The Dark Side of the Universe, Lecture Transcript and Course Guidebook (The Great Courses, Part 1 and Part 2)
Sean Carroll

Solving the Mysteries of the Universe
Stephen Hawking

Review Articles from Scientific American Magazine

Cline, David, "The Search for Dark Matter," March 2003.

Geach, James E., "The Lost Galaxies," May 2011.

Krauss, Lawrence, "Cosmological Antigravity," January 1999.

Milgrom, Mordehai, "Does Dark Matter Really Exist?" August 2002.

Rubin, Vera, "Dark Matter in the Universe," 1998.

Glossary

astrophysics The branch of astronomy concerned with the physical nature of stars and other celestial bodies, and the application of the laws and theories of physics to the interpretation of astronomical observations.

Big Bang The explosion of dense matter that, according to current cosmological theories, marked the origin of the universe.

Dark Matter Non-luminous material that is postulated to exist in space and that could take any of several forms including weakly interacting particles (cold dark matter) or high-energy randomly moving particles created soon after the Big Bang (hot dark matter).

electron A stable subatomic particle with a charge of negative electricity, found in all atoms and acting as the primary carrier of electricity in solids.

energy The property of matter and radiation that is manifest as a capacity to perform work (such as causing motion or the interaction of molecules).

fundamental particle (Also known as elementary particle) any of various fundamental subatomic particles, including those that are the smallest and most basic constituents of matter (leptons and quarks) or are combinations of these (hadrons, which consist of quarks), and those that transmit one of the four fundamental interactions in nature (gravitational, electromagnetic, strong, and weak).

galaxy A system of millions or billions of stars, together with gas and dust, held together by gravitational attraction.

gravity The force that attracts a body toward any other physical body having mass.

Higgs boson A subatomic particle whose existence is predicted by the theory that unified the weak and electromagnetic interactions.

interstellar gas (or interstellar medium; ISM) The matter that exists in the space between the star systems in a galaxy. It includes gas, dust, and cosmic rays. It fills interstellar space and blends smoothly into the surrounding intergalactic space.

Large Hadron Collider (LHC) The world's largest and highest-energy particle accelerator. It was built by the European Organization for Nuclear Research (CERN) with the aim of allowing physicists to test the predictions of different theories of particle physics and high-energy physics, and particularly prove or disprove the existence of the theorized Higgs boson and of the large family of new particles predicted by supersymmetric theories.

light Any wavelength of electromagnetic radiation including visible light, gamma rays, X-rays, microwaves and radio waves. Light is emitted and absorbed as particles called photons.

mass The quantity of matter that a body contains, as measured by its acceleration under a given force or by the force exerted on it by a gravitational field

matter That which occupies space and possesses rest mass.

particle accelerator An apparatus for accelerating subatomic particles to high velocities by means of electric or electromagnetic fields. The accelerated particles are generally made to collide with other particles, either as a research technique or for the generation of high-energy X-rays and gamma rays.

planet An astronomical object orbiting a star or stellar remnant that is massive enough to be rounded by its own gravity, is not massive enough to cause thermonuclear fusion, and has cleared its neighboring region of planetesimals.

proton A stable subatomic particle occurring in all atomic nuclei, with a positive electric charge equal in magnitude to that of an electron, but of opposite sign.

quark Any of a number of subatomic particles carrying a fractional electric charge, postulated as building blocks of the hadrons. Quarks have not been directly observed, but theoretical predictions based on their existence have been confirmed experimentally.

star A massive, luminous sphere of plasma held together by its own gravity.

subatomic particle Particles smaller than an atom (although some subatomic particles have mass greater than some atoms). There are two types of subatomic particles: elementary particles, which according to current theories are not made of other particles; and composite particles.

Supersymmetry theory a proposed symmetry of nature relating two basic classes of elementary particles: bosons, which have an integer-valued spin, and fermions, which have a half-integer spin.

Universe All existing matter and space considered as a whole; the cosmos. The Universe is believed to be at least 10 billion light years in diameter and contains a vast number of galaxies; it has been expanding since its creation in the Big Bang about 13.8 billion years ago.

xenon The chemical element of atomic number 54 (symbol: Xe), a member of the noble gas series. It is obtained by distillation of liquid air and is used in some specialized electric lamps.

Galaxies/Large Scale Structure

When the Universe was first born the distribution of matter was almost precisely uniform. Almost, but not quite. There were some tiny variations. Gravity is an amplifier of differences in density. If a location has greater density than another location then it will have a greater pull of gravity (since the force of gravity is proportional to the amount of matter). That greater gravity will pull more matter to it, winning in any tug-of-war, or simply pulling matter together faster than areas of lesser density. But if denser areas become even denser then their gravity will increase even more leading to even faster increase.

We can calculate what will happen and how, due to gravity, structure formation occurs in the universe from an initially (almost) featureless uniformity. It is from these denser regions that the structure we see in the universe first formed. Gravity formed objects in a "bottom-up" manner. The first objects to form were small, and low mass. Those then combined to form larger objects and even larger objects. Galaxies, the huge "cities of stars" that we see today formed in this way from smaller clumps of matter.

But the distribution of galaxies and even clusters of galaxies is not random. They are embedded in a "cosmic web" of material that is the signature of the formation of structure by gravity. Clusters of galaxies are connected by tendrils and sheets of matter, sometimes many millions of light years long. Between the clusters and filaments are empty voids where matter is extremely scarce, millions and billions of times scarcer than between the stars. Comparing the distribution of galaxies that we see with what our computer simulations predict can tell us how much and what kind of matter fills the universe.

Images of galaxies and the cosmic web. captions for the galaxy images can talk about the different types and sizes of galaxies.

Particle Physics

Normal matter is made up of atoms. For each of the more than one hundred chemical elements there is a corresponding type of atom. Chemistry is the study of how the atoms of these elements combine and interact. But what are the atoms made of? Atoms, it turns out, are composed of protons, neutrons and electrons. In combination they form atoms. The discovery of protons, neutrons and electrons in the early 1900s was a dramatic breakthrough. Instead of a hundred different kinds of atoms all the complexity could be stated in terms of just three basic particles. And yet as scientists studied these new "fundamental" particles they began to discover more and more. Instead of just three the numbers grew again to many dozens: the psi, the muon, the tau meson, the hyperon, etc. etc. Almost none of these particles occur in nature. They are only produced in extremely high speed collisions between other particles when there is a tremendous amount of energy available to create new particles. Particle physics became focused on building massive particle accelerators that are capable of whirling around these tiny bits of matter at speeds very close to that of light and slamming them into each other head on. By studying the exact patterns of particles produced in these intense collisions scientists can learn about what matter is made of. It is a bit like studying alarm clocks by slamming them together at high speed and looking at the debris that is left over. Except that the debris vanishes in a billionth of a second!

It was eventually realized that protons and neutrons, and many of the other newly discovered particles were composite themselves, made up of something more fundamental: quarks. Although not as simple as just three particles, we now understand that the whole zoo of particles that were discovered in the second half of the 20th century are made up of combinations of only 6 types of quarks and 6 types of "leptons" (particles like the electron). This "Standard Model" is one of the greatest scientific achievements of the 20th century. And yet, we know that it is incomplete. Astrophysical observations show that most of the mass of the Universe is in a form that cannot be composed of any of the particles of the Standard Model. Particle physicists have clues what this new form of matter might be, and are gearing up for searches using powerful new accelerators.