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ENCYCLOPEDIA ARTICLE

Dark matter

Particles or objects that exert a gravitational force but do not emit any detectable light. Dark matter is the dominant form of matter in our Galaxy. Astronomers have detected the presence of dark matter through its gravitational effects and have shown that dark matter is not composed of ordinary atoms. Particle physicists have suggested several plausible candidates for dark matter; planned experiments are capable of detecting these new particles.

Astronomical evidence for dark matter

A variety of astronomical observations imply that dark matter is ubiquitous; it is detected in dwarf galaxies, in spiral galaxies, and in elliptical galaxies. It is the dominant form of matter in galaxy clusters and leaves clear signatures in the large-scale distribution of galaxies and in the microwave background. Astronomers infer the presence of matter through its gravitational effects. Since they have not been able to detect any light directly associated with this matter, they have labeled it "dark matter."

Dark matter is also sometimes called the "missing matter." This is a misnomer since astronomers detect the mass but they are unable to detect the light associated with the matter.

Galaxy motions in clusters

Many galaxies are bound together in galaxy clusters. These galaxy clusters contain hundreds and sometimes thousands of galaxies. These galaxies are moving with very high relative velocities. Typical velocities are roughly 1000 km/s (600 mi/s), and some galaxies that appear to be bound to the cluster move at velocities as high as 2000 km/s (1200 mi/s). Within an individual galaxy, stars and gas move much slower with typical velocities of only 200 km/s (120 mi/s).

As early as the 1930s, F. Zwicky recognized that clusters must be very massive to have a strong enough gravitational field to keep these high-velocity galaxies bound to the cluster. Zwicky noted that the inferred mass was much larger than the mass in stars. The result was so surprising that most of his colleagues ignored his conclusion. Current estimates suggest that stars comprise only 1% of the mass of the cluster (**Fig. 1**). See also: Galaxy, external

Sloan Digital Sky Survey image of the Perseus galaxy cluster. Galaxies in the cluster are moving relative to each other at velocities of thousands of kilometers per second. Since the cluster appears to be gravitationally bound, this implies that the cluster has a mass of 10^{11} solar masses, roughly 100 times the mass contained in stars. (*Robert Lupton; SDSS Collaboration*)

Galaxy rotation curves

Most galaxies, including our own Milky Way, are spiral or disk galaxies, where cold atomic and molecular gas (primarily hydrogen) settles into a rotating disk. Much of the molecular gas is found in spiral arms. These spiral arms are active sites of star formation. See also: Milky Way Galaxy

The gas and stars in disk galaxies move on nearly circular orbits. The Sun is moving on a nearly circular orbit around the center of the Milky Way Galaxy. To keep material moving on a circular orbit, centrifugal acceleration must balance gravitational acceleration. This balance can be expressed by the equation below,

$$\frac{V^2}{R} = \frac{GM}{R^2}$$

where V is the velocity of the gas or stars, R is the distance from the center of the galaxy, G is Newton's constant, and $M(R)$ is the mass contained within radius R. See also: Centripetal force; Centrifugal force

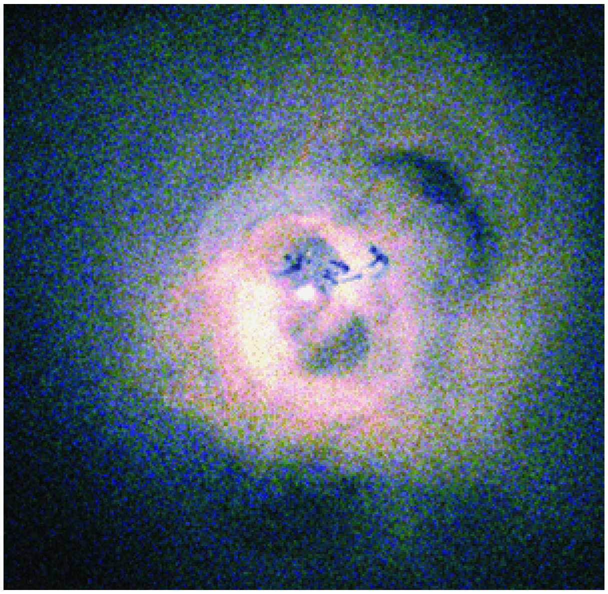
Astronomers can measure the velocity of gas and stars in other galaxies through the Doppler effect. In the 1960s and 1970s, Vera Rubin pioneered optical observations of the motions of stars near the visual edges of galaxies. She found that the stars were moving rapidly. This large velocity implied the presence of hundreds of millions of solar masses of matter where little light was detected. Radio observations of the motions of neutral gas beyond the visual edge of spiral galaxies confirmed this remarkable result: Most of the mass in a galaxy is not in its disk of young stars, but rather in a halo composed of dark matter (**Fig. 2**). See also: Doppler effect

Sloan Digital Sky Survey image of galaxy M101. Measurements of the velocities in the disk of the galaxy imply the presence of enormous amounts of mass out toward the edge of the disk. (*Robert Lupton; SDSS Collaboration*)

Hot gas in elliptical galaxies and clusters

X-ray satellites have detected copious amounts of hot gas in elliptical galaxies and in galaxy clusters. Since the thermal pressure in this 1–10 million degree gas balances the gravitational field of the galaxy, measurements of the density and temperature profiles of the gas can be used to directly measure the mass distribution in these galaxies. These measurements reveal that the dark matter problem is ubiquitous: Stars can account for only a small fraction of the mass in elliptical galaxies. Observations of x-ray gas in clusters confirm Zwicky's inference that stars account for only a small fraction of the mass in a cluster (**Fig. 3**). See also: X-ray astronomy

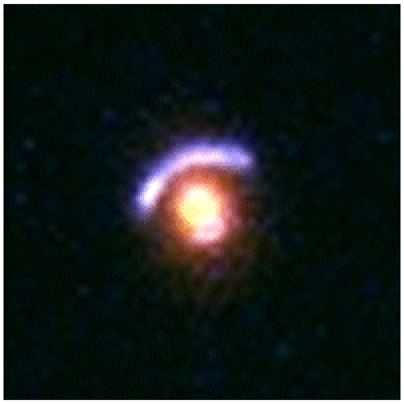
Chandra X-ray Observatory image of hot gas in the Perseus galaxy cluster, indicating that stars account for only a small fraction of the mass of the cluster. (*NASA/Chandra X-ray Center/Institute of Astronomy/A. Fabian et al.*)



Gravitational lensing

John Wheeler has remarked that "General relativity is simple: Matter tells space how to curve; the curvature of space tells matter how to move." Since mass curves space and distorts the path of light, images of galaxies that are behind rich clusters can be used to infer the distribution of mass in clusters. The masses in clusters distort background galaxies into arcs whose orientations are very sensitive to the distribution of matter in the cluster. Observations of gravitational lenses detect the presence of significant amounts of dark matter, and are consistent with the x-ray and optical observations of the same clusters (**Fig. 4**). See also: Gravitational lens; Relativity

Hubble Space Telescope image of a lensed background source in the form of an extended arc about an elliptical lensing galaxy. By measuring the distortions in the background, the mass of the foreground lensing galaxy can be inferred. (*Kavan Ratnatunga, Carnegie Mellon University; NASA*)



Novel nature of dark matter

The astronomical evidence discussed above shows that most of the mass in galaxies is not in the form of luminous stars and is consistent with a wide range of plausible candidates. Most astronomers assumed that the dark matter was similar to the “ordinary stuff” that makes up stars: protons, neutrons, and electrons. Cosmologists often refer to this “ordinary stuff” as baryonic matter. (Unfortunately, cosmologists use the term “baryonic matter” to refer to protons, neutrons, and electrons, while particle physicists, more correctly, refer to only protons and neutrons as baryonic matter.) Astronomers have searched for various possible forms of ordinary matter, including gas, dust, and low mass stars, but they have been unable to detect it. See also: Baryon

Cosmological observations can measure the density of atoms in the early universe. These observations imply that baryonic matter can account for only one-sixth of the mass in galaxies. These observations imply that most of the mass in galaxies is in the form of some novel and not yet identified form of matter.

Gas

Gas can be detected through either emission or absorption. Astronomers have measured the mass in atomic gas through observations of the 21-cm line and molecular gas through millimeter observations of carbon monoxide (CO) clouds. These observations suggest that only 1% of the mass of the Milky Way Galaxy is in cold gas in the galactic disk. See also: Interstellar matter

X-ray satellites can detect 1–100 million degree gas through its thermal bremsstrahlung emission. These observations reveal that most of the baryonic matter in rich clusters is not in stars but in hot gas. In some rich clusters, there is ten times as much mass in hot gas as in stars. While significant for the evolution of the cluster, only 10–20% of the mass in a cluster is in hot gas. Dark matter accounts for most of the remaining 80–90%. See also: Bremsstrahlung

Low-mass stars

While massive stars can be easily detected through their light, very low mass stars and planet-size objects are so dim that they can evade detection by optical telescopes. Astronomers, however, can detect these stars through their gravitational effects.

When a low-mass star passes in front of a distant star, it serves as a gravitational lens. This lensing brightens the image of the background star. Using large-area cameras capable of monitoring millions of stars, astronomers have searched for and detected these effects as low-mass stars pass in front of stars in the Large Magellanic Clouds and in front of the Milky Way bulge. While these observations have detected hundreds of low-mass stars through their gravitational effects, the number of events are consistent with models of the Milky Way Galaxy and imply that there are not enough low-mass stars to account for the dark matter.

Deuterium and helium

During the first minutes of the big bang, all of the neutrons in the universe combined with protons to make deuterium (one proton and one neutron). Two deuterium nuclei then collided to make helium (two protons and two neutrons). Most of the helium and deuterium in the universe was produced during the first few minutes of the big bang, and thus deuterium and helium can be said to be fossils from that time. The cosmological abundance of deuterium depends on the density of baryons (protons and neutrons) in the early universe: the more baryons, the lower relative abundance of deuterium. Astronomers use measurements of the ratio of the relative number of deuterium nuclei to provide a direct estimate of the density of atoms in the universe. See also: Big bang theory

These observations imply that ordinary matter makes up only 4% of the energy density of the universe. These observations suggest that dark matter is not composed of protons and neutrons (or of nuclei made of protons and neutrons).

Microwave background fluctuations

Measurements of microwave background fluctuations are an important probe of the composition of the universe. The tiny variations in temperature seen by the *Wilkinson Microwave Anisotropy Probe* (and by ground and balloon-based microwave experiments) were produced during the first moments of the big bang. The statistical properties of these fluctuations depend on the composition of the universe: the more atoms, the smoother the shape of the fluctuations; the more matter, the higher the relative amplitude of small-scale fluctuations. The current observations confirm that ordinary matter makes up only 4% of the energy density of the universe and also imply that dark matter comprises 25% of the energy density of the universe See also: Cosmic background radiation; Wilkinson Microwave Anisotropy Probe

Dark matter candidates

The big bang theory implies that the early universe was very hot and very dense, the perfect environment for creating particles through collisions. The densities and temperatures in the first microsecond of the big bang exceed the energies achieved in even the most powerful particle accelerators. Many cosmologists suspect that the dark matter is composed of some yet undiscovered fundamental particle that was produced in copious numbers during the first moments of the big bang.

Supersymmetry

The most popular dark matter candidate is the neutralino, a new particle posited by the theory of supersymmetry. Supersymmetry is an extension of the standard model of physics and is a vital element in almost all attempts to unify the forces of nature and in attempts to connect gravity and quantum mechanics.

Modern particle physics is based on the symmetries observed in nature. For example, all particles have antiparticles. The positron is the antiparticle of the electron. The antiproton is the antiparticle of proton. While seemingly bizarre, antimatter has not only been produced in the laboratory and detected in space, but now plays a major role in medical imaging (PET scans). See also: Antimatter; Medical imaging; Symmetry laws (physics)

Particle physicists have speculated on the existence of a new, not yet confirmed symmetry: supersymmetry. Supersymmetry implies that particles such as electrons and positrons have partners called selectrons and spositrons. These superparticles have the opposite statistical properties to ordinary matter. Selectrons behave like photons, while the supersymmetric partner of the photon, the photino, behaves quantum mechanically like an electron. This new symmetry has many aesthetic attractions and helps to explain the relative strength of the fundamental forces of nature. These new particles interact weakly with ordinary matter and have so far escaped detection. (They also may not exist.) See also: Quantum statistics;

Supersymmetry

Supersymmetry implies the existence of a new stable particle: the neutralino. The neutralino would have been produced in abundance during the first moments of the big bang. During the first nanosecond of the big bang, there were as many neutralinos as photons in the universe. While the number of neutralinos was reduced as they annihilated into ordinary matter, the current best estimates of their predicted residual abundance imply that they could be the dark matter. See also: Weakly interacting massive particle (WIMP)

The primary scientific goal of the new Large Hadron Collider (LHC) at CERN in Switzerland, scheduled for start-up in 2007, is to detect the experimental signatures of supersymmetry. By colliding nuclei at velocities very close to the speed of light, the LHC aims to recreate some of the conditions in the big bang. The LHC may be able to provide direct evidence for the existence of supersymmetry and may even be able to produce dark matter particles in the laboratory. See also: Particle accelerator

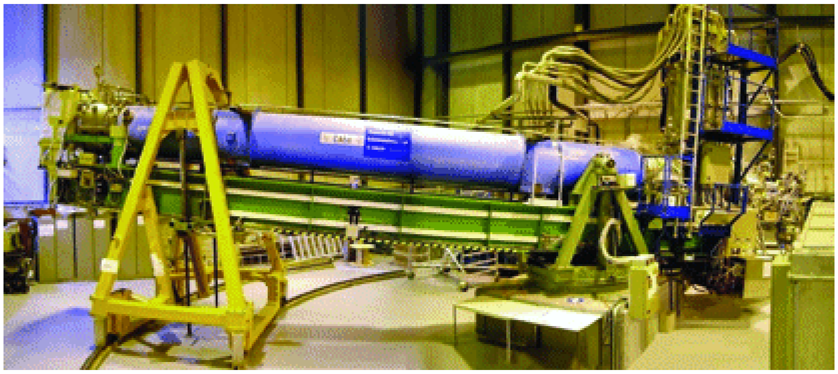
Deep-underground experiments may also detect dark matter. If the neutralino is the dark matter, then hundreds of millions of these particles are streaming through our bodies every second. Because the neutralino interacts so weakly with ordinary matter, our bodies (and our detectors) are nearly transparent. These particles, however, do have rare weak interactions. In a kilogram detector, the dark matter particles may have a few collisions per day. These collisions are difficult to detect since each collision deposits only 10^{-3} (10^{-15} erg) of energy. Physicists have built a number of very sensitive low-background experiments capable of directly detecting neutralinos. Because the experiments need to be shielded from cosmic rays and other terrestrial sources of background signal, they must operate in deep-underground mines and tunnels.

Gamma-ray satellites may also be able to indirectly detect the neutralino. While the neutralinos interact weakly, occasionally one neutralino collides with another neutralino. This collision produces a shower of particles and radiation. Several on-going and planned experiments are looking for this dark matter annihilation signal. See also: Gamma-ray astronomy

Axions

The axion is another hypothetical particle, which was invented to explain one of the symmetries seen in the strong nuclear interaction. If this explanation is correct, then axions would have been produced copiously during the first microsecond of the big bang. While axions interact very weakly with ordinary matter, they can be converted into ordinary photons in the presence of a very strong magnetic field. Experimentalists are using very strong fields to search for the axion (**Fig. 5**).

CERN Axion Solar Telescope (CAST), which uses a 9-tesla, 10-m (33-ft) prototype dipole magnet for CERN's Large Hadron Collider, enhanced by the use of a focusing x-ray telescope, to search for axions from the Sun's core. (*CERN*)



Black holes

If black holes were produced in large numbers during the first moments of the big bang, then they would be plausible candidates for the dark matter. Currently, there are no viable scenarios for producing large numbers of black holes in the early universe. However, since there are significant uncertainties in our understanding of physics during the first microsecond of the big bang, some astronomers consider black holes to be a viable dark matter candidate.

If the dark matter were composed of black holes and the black holes were significantly more massive than the Sun, then the black holes could be detected through their gravitational effects on galaxies and globular clusters, or through gravitational microlensing (discussed above in connection with the detection of low-mass stars). However, low-mass black holes could easily evade any current (and planned) observational searches. See also: Black hole

Failure of general relativity

Many astronomers have speculated that the discrepancy between the mass seen in stars and gas and the mass inferred by applying general relativity (and Newtonian gravity, its low-velocity simplification) to astronomical observations is not the signature of some new exotic particle, but instead is the observational signature of the breakdown of general relativity. Classical Newtonian physics works well in daily life: Quantum mechanics is usually important only at very small scales and general relativity is only important on very large scales and near massive objects such as black holes and neutron stars. Perhaps the dark matter problem is the observational signature of the failure of general relativity. The discovery of dark energy strengthens the motivation for considering these alternative models.

Modified Newtonian dynamics (MOND), developed by Mordehai Milgrom and Jacob Bekenstein, is the most carefully examined alternative gravitational theory. It has the advantage of explaining galaxy rotation curves without resorting to dark matter. However, MOND has difficulties fitting the data implying the existence of dark matter in clusters and is inconsistent with WMAP's observations of microwave background fluctuations. See also: Cosmology; Universe

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Additional Readings

- Wilkinson Microwave Anisotropy Probe
- WMAP Cosmology 101: Matter in the Universe
- OGLE (The Optical Gravitational Lensing Experiment)
- Hubble's Top Ten Gravitational Lenses
- Chandra Probes Nature of Dark Matter
- Large Hadron Collider
- Cryogenic Dark Matter Search (CDMS)

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