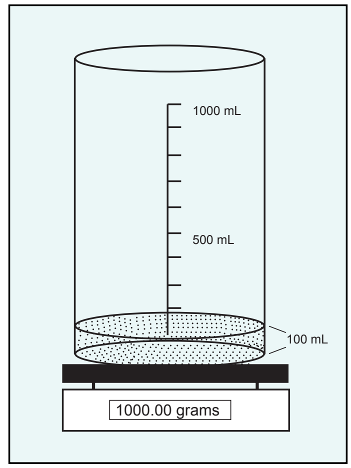
Cosmic Chemistry: Cosmogony

Dark Matter—More Than Meets The Eye

STUDENT TEXT



In the activity, "Dark Matter—A Milky Way Surprise," you encountered a situation that appears to be inconsistent with our normal experience. Some scientists call these situations "discrepant events."

If a beaker contains 100 mL of water, we expect the water to have a mass of 100 grams, since the density of water is 1.00 g/mL. But the balance showed the contents of the beaker to have a mass of 1000 grams. Ah, there must be more to this situation than meets the eye.

A similar "discrepant event" has been observed in the universe. In recent years, theory and observation alike have indicated that at least 90% of matter (and perhaps as much as 99% of the mass of the universe) is **dark matter**, **nonluminous matter**, matter that cannot be observed with telescopes. It is invisible, not because it is far away, but because it neither emits nor absorbs light. So, could one answer to our beaker situation be that 90% of its contents were dark matter?

If we can't see it, how have scientists been able to find dark matter? Spectroscopy didn't help. Observations in a variety of spectral ranges—ultraviolet, visible, infrared, or x-ray—have been unable to detect most dark matter. And no one sent up a set of balances in a space probe to measure its mass. Dark matter was "discovered" as a result of another discrepant event.

Our solar system as a model

In the "Mathematical Models" activity of this Genesis module, you worked with a table of the solar system planets, their distances from the sun, and the time it takes the planets to travel around the sun. You found that the farther the planet was from the sun, the longer it took for the planet to travel around the sun.

In the Genesis education module, "*Cosmic Chemistry: Planetary Diversity*," we learned that more than 99% of the mass of the solar system is in the sun, and that the sun's gravitational attraction for the planets decreases as the square of their distances from the sun. We also learned that the sun's gravitational attraction for planets is greater for those close to it than for those who are farther away. So, in our solar system, the inner planets move more rapidly in orbit than do those farther out. Mercury, whose solar distance is 0.39 of Earth's distance, orbits the sun with a velocity of 47.9 km/sec. Pluto, which is 100 times farther from the sun (39 Earth distances), has a velocity of 4.7 km/sec, one-tenth that of Mercury. This is a characteristic of all orbital systems where the mass is concentrated inside the orbit, according to Kepler's third law of planetary motion.

Most astronomers thought that rotating galaxies should show the same characteristics as our solar system. And they *assumed* that the center of a galaxies' mass was located where the greatest amount of **luminous matter**—**bright matter,** the matter we can see—was found. After all, our sun, carrying the planets with it, orbits the Milky Way galaxy with a speed of 200/km sec.

A Milky Way surprise!

Imagine scientists' surprise, however, when they found that there are individual stars and concentrations of gas in our galaxy at *greater* distance from the luminous nucleus than our sun that have rotational velocities the same as or *greater* than that of our sun! Kepler's third law of planetary motion says that these stars should move slower, the further out they are. This is the paradox.

Scientists now think that this is an indication that most of the mass of the Milky Way galaxy is **not** located in the luminous nuclear region, as we previously assumed. It appears that nonluminous mass (dark matter) is less concentrated in the center of the galaxy than are the visible stars and gas. In fact, evidence shows that the average density of the nonluminous matter at large distances from the center may be as much as 1000 times greater than the mean density of the mass in the universe. So, dark matter may be clumped around galaxies, in much the same way that we found matter clumped around voids in "The Spongy Universe."

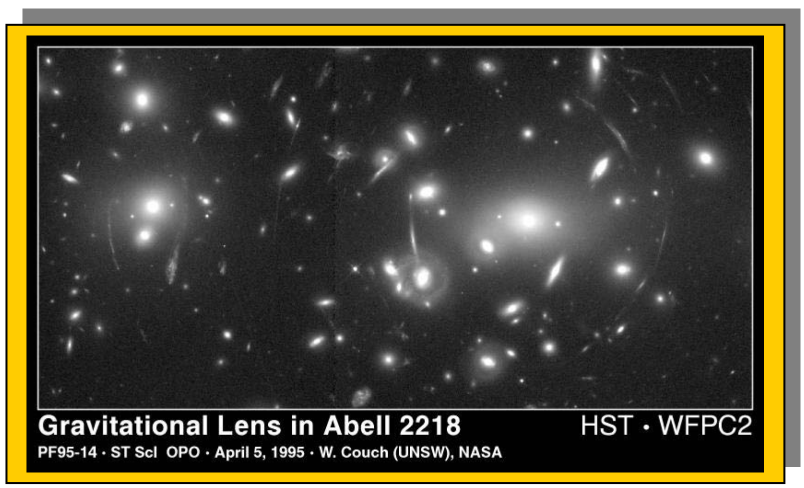
How do we detect dark matter?
The strongest evidence for the existence of dark matter comes from studying **galactic dynamics,** the orbital motions or the rotation of stars and galaxies, using both old and new techniques. A **spectroscope** can be used to detect composite radiation spectra of individual stars and gas in a particular location of a spiral galaxy. Measurement of the displacements of spectral lines in successive exposures is used to calculate the velocity of stars corresponding to that location in the galaxy. (For more information on emission spectroscopy, see Student Text, "Are You Coming or Going?" in this module and Student Text, "Electromagnetic Radiation," Genesis Module, *Cosmic Chemistry: The Sun and Solar Wind*.)

When starlight from external galaxies is too faint to produce a good spectrum, one can measure velocities from the **emission lines** arising in the ionized gas clouds surrounding the hot young blue stars which outline spiral galaxies.

Radio astronomers can detect a 21-cm **radio emission** from cold hydrogen clouds in galactic disks, the plate-shaped part of a spiral galaxy, half again beyond the point where the disk can be detected by optical instruments. This radiation is not obscured by the prominent dust lanes often seen in spiral galaxies. The solar system has no such massive disk of invisible stuff stretching out past the orbit of outer planets, but many galaxies apparently do.

X-ray emissions can be used to detect the hot gases surrounding giant elliptical galaxies in the centers of clusters. The x-ray energy, which indicates temperature and velocities of atoms, is also an indication of the lower limit of **escape velocity** of the galaxy. The escape velocity is directly related to the mass of an object, (See www.genesismission.org/educate/scimodule/PlanetaryDiversity/plaandiv_pdf/OuchThatHurtsST.pdf) so it can be used to determine the minimum mass of the galaxy. In most cases, the mass turns out to be 10 times the mass of the visible stars in the galaxy. From this it can be inferred that the galaxy is mostly dark matter.

Gravitational lensing is a technique that takes advantage of the fact that matter distorts the space surrounding it. For example, when light from a quasar travels toward us in space, it may pass to either side of an intervening cluster of galaxies. The warping of space in gravitational fields surrounding the cluster can act as a lens, with the result that we see two images of what is one quasar. The strength of the gravitation field is a measure of how much mass there is in the cluster and where it is centered. This center is usually outside the luminous center, again suggesting that at least some galaxy clusters are primarily dark matter.



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Massive objects (sun, galaxies, dark matter. etc.) can actually bend space enough to focus light from distant stars, so that the stars appear to brighten when a dark object passes in front of it. These **microlensing** events, caused by dark objects in the **galactic halo**, can be detected by charge-coupled devices.

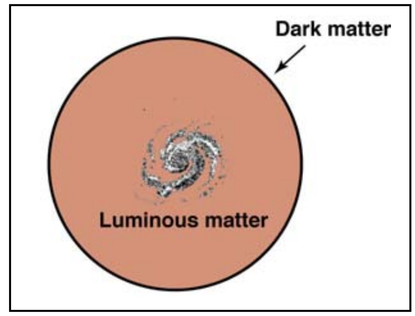
Charge-coupled devices (CCDs) are made of light-sensitive silicon chips having an arrangement of light-sensitive spots called pixels. Each pixel reports digitally, in real time, to a computer; so CCDs make motion pictures, which record variations in brightness of stars due to massive objects passing through the line of sight leading from the star to the telescope. CCDs are more sensitive than photographic emulsions, and they have better resolution. Thus one can take a picture of galaxies that are further away with CCDs.

How much of the matter in the universe is dark?
Since the 1990s, there has been growing acceptance of the idea that perhaps 90% of the mass in the universe is nonluminous. Dark matter exists around individual galaxies and between galaxies in clusters. Based on a variety of

observations on a variety of distance scales, the larger the piece of the universe sampled, the greater the percentage of dark matter found.

Galaxies

Figure 1



Most astronomers now assume that dark matter is distributed more or less in the same space with the visible galaxies. Galaxy dynamics tells us that across the visible part of a galaxy, the luminous disk is matched by an equal nonluminous **halo** mass, which is a spherical aggregation of stars, globular star clusters and thin gas clouds centered on the nucleus of a galaxy and extending beyond the known extremities of the galactic disk. (See Figure 1.) Evidence has been found for the presence of lots of dark matter both in the disk and halos of **spiral** galaxies.

In our own galaxy, the total mass of stars in the sun's neighborhood is about one-third less than that calculated by the dynamics. Beyond the visible galaxy out to the largest distance to which rotation velocities have been measured, there is possibly five or ten times as much dark matter as luminous matter. Studies of the orbital velocity of stars near the sun revealed that there is at least twice as much mass in the Milky Way galactic disk as can be accounted for by adding up the mass of all stars and interstellar clouds. While the solar system does not have any detectable evidence for dark matter, our galaxy is composed of perhaps 90% dark matter.

Elliptical galaxies have neither disks nor spiral arms and they contain less interstellar dust and gas than is found in spiral galaxies. Some elliptical galaxies are as spherical as basketballs and others are cigar-shaped. Elliptical galaxies have little or no net rotation since their stars orbit in a more complicated fashion. Applying the same type of galaxy dynamics that works so well for spiral galaxies is not practical for elliptical galaxies. However, studies based on x-ray-emitting gas surrounding giant ellipticals in the centers of clusters found that these galaxies are about 90% dark matter.

Dwarf galaxies are full of dark matter. They have low mass, corresponding to only 1 million to 10 million suns; this is thousands of time less than average spiral galaxy. They also have low escape velocities, so material from supernovae and the stellar wind from red giant stars easily escapes from a dwarf galaxy, leaving it poor in stars but rich in dark matter.

Groups and Clusters

In groups and clusters of galaxies, astronomers find dark matter in abundance. Several sorts of evidence indicate that clusters of galaxies are at least nine-tenths dark matter. Dynamical and x-ray examination of the Coma Cluster show that it is at least 90% dark matter and gravitational lensing also suggests that at least some galaxy clusters contain up to 90% dark matter.

A similar situation pertains to galaxies orbiting near the outskirts of a galaxy cluster. Their velocities index the total mass of the cluster within each galaxy's orbit and reveal the presence of a much stronger gravitational field than can be accounted for by adding up the mass of all the stars and other bright objects in the cluster.

So, the larger the scale on which we sample the universe, the greater the proportion of dark matter seems to be.

Is dark matter made of MACHOs, WIMPS, or something else?

MACHOs and **WIMPs** are dark matter jargon**. MACHOs** stands for Massive Compact Halo Objects. Halo refers to **galactic halos** described in the above section about galaxies. MACHOs are made of **baryons**, (Greek for "heavy") a group of particles that includes protons and neutrons, which are made of quarks. Most of mass of ordinary matter that we can see and touch of which we are made are baryons. Baryonic matter makes up galaxies, stars, and atoms, has been processed in stars, and has evolved along with the universe.

Table 1. Elementary particles that were main characters in this cosmogony module.

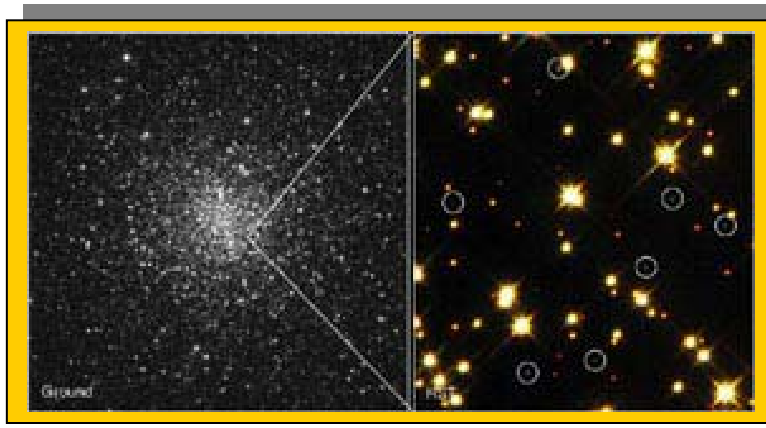
Baryons (MACHOs)	Leptons (WIMPs)	
protons	electrons	photons
neutrons	neutrinos	gluons

WIMPs are **leptons** (Greek for "light"). The term is an abbreviation for Weakly Interacting Massive Particles, which includes electrons, which have very little mass, and neutrinos, which we think have virtually zero mass.

Bosons are force-carrying particles. This family includes photons, the **quanta** of electromagnetic force and gluons, quanta that carry the strong nuclear force.

Baryons – one possibility
One possibility is that all dark matter is baryonic; that is, made of protons and neutrons—MACHOs! Dark matter may be dwarf stars too dim to be observed. Or they could be cold planet-like objects with masses about 1/1000 that of the sun. Or maxi- or mini- black holes. Or massive cold gas clouds. All these phenomena are baryonic.

There is some observational evidence for the existence of MACHOs. Because they can warp space enough to focus light from a distant star, MACHOs have played a critical role in a number of microlensing events in the observation of the Large Magellanic Cloud. The diameters of these MACHOs indicated that most of them were either white or brown dwarf stars. Surely at least *some* dark matter is baryonic.



Left: Globular cluster M4. Right: Eight dwarf stars

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The study of gravitational microlensing is in its infancy, but as techniques improve, we may be able to map galactic halos in greater detail. If the halos of major galaxies have radii of three to four million light-years, then baryonic matter in the halos might account for the dark matter thought to exist in clusters of galaxies. In that case, dark matter would consist of nothing but MACHOs. If, however, the halos are smaller, there may still be plenty of baryonic dark matter out there—perhaps in the form of dark galaxies.

But, scientists' mathematical predictions of the total mass of protons and neutrons resulting from the formation of matter in the early epochs of the universe (See Student Text, "Models and Thought Experiments") make it unlikely that there was enough baryonic dark matter formed in the Big Bang to explain the dynamics of a galaxy cluster.

Enter the WIMPs?
At least some of dark matter must be made of familiar baryonic MACHO stuff, but most of it may be of an exotic nature as yet unknown. Remember that in "The Spongy Universe" activity, we found that large voids exist in the cosmos. We do not even know IF anything is present in the voids. Are they empty of all matter, or only void of baryonic matter?

Nonbaryonic forms of matter—WIMPs**—**have been suggested. Neutrinos were the first appealing WIMP candidates for the dark matter. They are nonbaryonic particles that interact with ordinary matter only through the weak nuclear force. It is thought that lots of neutrinos were released in the events of the early epochs of the cosmos. We found in the Genesis Module, "*Cosmic Chemistry: The Sun and Solar Wind*," that there is evidence of their formation in the core of our sun.

So, neutrinos are known to exist but it is generally assumed that they have no mass, which doesn't help explain the source of the large proportion of cosmic mass attributed to dark matter. The cosmology predicted by some other WIMP particles is complex and none of them has properties which predict all of the observations.

So where does that leave us?
The present state of affairs is this. We know that there is a great deal of dark matter in the universe. We are fairly certain that most of it is not made of baryons. In fact, we have ruled out every ordinary type of candidate particle we know of and can produce in our accelerator laboratories.

So does dark matter exist in some form which we have not seen and does it have properties with which we are not familiar? Some scientists think that there are still some dark matter candidates that need to be explored. These include some counterparticles of those which we are familiar: squarks, theoretically related partner of the quark, and the photino (partner of the photon).

The **axion** is a theoretical elementary particle with a mass less than one millionth of an electron that has never been detected. If it exists, dark matter could consist of large collections of axions.

It may also be that most of the universe is made of dark, nonbaryonic material that is part of a whole universe of shadow matter that exists in parallel with our own. If this is true, the two universes separated when gravity became the major force in our early universe. If this is true, then shadow particles interact with us only through the force of gravity. This makes them an ideal candidate for dark matter.

Recently astronomers have theorized that if our galaxy is really full of dark matter in the form of WIMPs, then during its lifetime, our sun would have absorbed a fair number of them. The consequences of WIMPs being part of the sun's composition could lead to different bulk properties of the sun and to recalculating the theoretical number of neutrinos emitted from it. Neither of these consequences is consistent with our current standard solar model. (See Genesis Module, "*Cosmic Chemistry: The Sun and Solar Wind*.")

Cosmologists continue to be confronted with a new challenge—to chart dark matter and to identify its characteristics.