Dark Matter: The Matter We Cannot See that Dominates the Universe

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The concept of dark matter is one of the most exciting, compelling, mysterious, and perhaps disturbing ideas that has emerged from modern astrophysics. The term dark matter means, quite simply, matter that produces so little light that we cannot see it. We can, however, detect the presence of dark matter even when it does not generate much or any light. If all forms of dark matter were simply normal matter that generated very little light, it would not be such a powerful and bizarre concept. Instead, in twenty-first century terms, we know of several kinds of dark matter, some familiar, others exotic.

Some kinds of dark matter are objects composed, ultimately, of subatomic particles that we (or perhaps just most physicists) understand from laboratory experiments and have become familiar with, at least by name: protons, neutrons, mesons, and a host of other particles composed of quarks, as well as electrons, muons, tauons, and neutrinos, which are not composed of quarks. Depending on the combinations of quarks in a particle, those particles composed of quarks can respond to some or all of the four forces: the strong nuclear force, the weak nuclear force, the electromagnetic force, and the gravitational force. Most other kinds of subatomic particles respond to three of the forces but do not respond to the strong nuclear force, while neutrinos respond only to two of the forces, the weak nuclear force and gravity.

Tracing the progress of astronomers' ideas about the evidence for dark matter over the course of the last two and a half centuries is very useful for motivating and understanding the need for something called dark matter, especially for exotic dark matter, even though some of the first-identified forms of dark matter are no longer considered dark matter. Our problem can be reduced to this question: *How do we know something is out there in the heavens if we cannot see it?* After all, as we are fond of saying, seeing is believing.

The dark matter story began in 1783, when British geologist and amateur astronomer, the Reverend John Michell, imagined the possible existence of a star 500 times bigger in radius than the Sun but with the same average density as the Sun. He calculated that “all light emitted from such a body would be made to return toward it, by its own proper gravity.” He elaborated, “If there really should exist in nature [such] bodies … since their light could not arrive at us, we could have no information from light. Yet if any other luminous bodies should happen to revolve about them, we might still perhaps from the motions of these revolving bodies infer the existence of the central ones.” In simpler terms, such a star would be dark. This star would contain matter that we could not see because no light emitted by this star could ever reach us; however, we could readily infer the existence of the dark star from its gravitational influence on other objects.

Reverend Michell's dark bodies do exist. We call them black holes. Some black holes, for example those that form when some massive stars die, form out of normal matter; others may have formed from exotic dark matter. But since we cannot see inside a black hole, we have no way of knowing anything about the character of the mass out of which any one black hole is made.

Half a century later, Friedrich Wilhelm Bessel suggested that the stars Procyon and Sirius slalomed slowly across the sky in a way that only made sense if each of these stars was orbiting an unseen companion. When Alvan Clark detected Sirius B in 1862, these previously invisible companions changed in our understanding of them from dark and unseen to merely faint and hard to detect. These dark companions are now known as white dwarfs, and we do not consider white dwarf companions to nearby stars to be dark matter. However, at greater distances white dwarfs remain impossible to detect via the light they emit because they are so faint; distant white dwarfs, though they emit light, therefore remain a dark matter candidate and could be an important component of the dark matter in galaxies.

In 1845, the British mathematician John Couch Adams and the French astronomer Urbain Le Verrier independently used the known problems with the orbit of the planet Uranus to predict the existence and calculate the orbital path around the Sun of an unseen planet. One year later, when Johann Galle, working at the Berlin Observatory, looked in the direction predicted by Le Verrier for the location of the mystery planet he found Neptune. This planet was never truly dark; it just was too faint to be detectable without the aid of a telescope and, as a result, escaped detection until someone looked carefully in the right direction with a telescope. Astronomers do not think a significant amount of mass remains to be found in our solar system in the form of distant faint planets, dwarf planets, comets, Kuiper Belt objects, or even a distant companion star. However, if the galaxy is populated by a large number of Neptune-like and Jupiter-like giant planets that do not orbit stars, this population of objects could be an important component of the dark matter in galaxies and likely will remain all but undetectable in coming decades.

White dwarfs emit very little light because they are small in comparison to normal stars; planets emit very little light because they are very small and cool in comparison to stars; black holes emit no light because light cannot escape the gravitational pull of a black hole. In all of these cases, hard-to-see objects produce or reflect light. For this reason, all of these kinds of objects are forms of dark matter made of normal matter. Together, they represent two centuries of work wrapped around a single, very important concept: *matter can be present in the universe whose existence we can infer from the behavior of other objects but whose presence cannot be discerned in light emitted from or reflected by that matter itself because these objects emit or reflect very little light*.

Cold dark matter

Fritz Zwicky was an astronomer who worked at Cal Tech, in Pasadena, California, from the 1920s into the 1970s. In 1933, Zwicky measured the velocities of galaxies in the Coma Cluster of galaxies and found that they were moving extremely fast, up to several thousand kilometers per second[1]. According to Zwicky's calculations, these galaxies had velocities that were so large that most of the Coma Cluster galaxies should have run away, or escaped, from the cluster[2]. Quite simply stated, the Coma Cluster should not exist anymore, yet it does. Zwicky wondered why.

Zwicky's calculations were based on his observations of all the luminous matter — the galaxies — in the cluster. Of course, in 1933 'luminous' meant 'producing light our eyes can see,' since gamma ray astronomy, X-ray astronomy, ultraviolet light astronomy, infrared astronomy, millimeter wave astronomy, and radio astronomy had not been invented yet. Using the luminosities of these galaxies in visible light, Zwicky estimated the total mass of the Coma Cluster; using this mass estimate, he calculated how fast a galaxy could move in that environment and still be bound by gravity to the cluster (the escape velocity). A fast-moving galaxy should escape from the cluster while a slow moving galaxy would remain part of the cluster. Since even the galaxies moving much faster than the apparent escape velocity had not escaped, Zwicky suggested that the Coma Cluster must contain an enormous amount of unseen matter and that the true escape velocity must be much greater than the value he calculated from his measurements of the total amount of luminous matter. By his estimate, the Coma Cluster must contain four hundred times more mass, all of it unseen, than his estimate for the mass of all the luminous matter, in order to provide the gravitational pull that would bind even the fastest moving galaxies to the cluster forever. Modern improvements on and corrections to Zwicky's work have reduced the need for an over-abundance of unseen matter to a factor of fifty, rather than four hundred, but the conclusion remains solid: as much as 98 percent of the mass of the Coma Cluster is not producing enough visible light to be seen. What could that mass be? Black holes? White dwarfs? Jupiters?

Because this unseen matter, like the galaxies, had not escaped the Coma Cluster, Zwicky realized that whatever this matter was, it must be composed of objects that have velocities comparable to or smaller than those of the galaxies themselves (else the unseen matter would have escaped the galaxy cluster) and therefore veleocities much smaller than the speed of light. In an astrophysical environment, slow moving particles or objects — where the adjective 'slow' is offered as a comparison to the speed of light — are called 'cold;' in contrast, fast moving particles are called 'hot.' Since this unseen material was 'cold' in the logic of astrophysics, Zwicky called this material dunkle (kalte) materie, or dark (cold) matter.

With Zwicky's study of the Coma Cluster, cold dark matter entered the twentieth century conversation, and by 1999 astrophysicist Sidney van den Bergh would write that this

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[1] For comparison, Earth orbits the Sun at 30 kilometers per second while the Sun orbits the center of the Milky Way Galaxy at a speed of about 200 kilometers per second.

[2] The escape velocity (v_{esc}) is the speed needed to escape the gravitational grasp of an object. The value of v_{esc} depends on both the mass and size of the object. The escape velocity from the surface of Earth is 11 kilometers per second; from the surface of the Sun $v_{esc} = 600$ kilometers per second; and from the Milky Way galaxy (starting at the position of the Sun), $v_{esc} = 550$ kilometers per second.

work of Zwicky's "may turn out to have been one of the most profound new insights produced by scientific exploration during the 20th century." Few now would disagree with van den Bergh, but few in the 1930s paid much attention to Zwicky's surprising results. One who did, Sinclair Smith of Mt. Wilson Observatory, in 1936 found a result for the Virgo Cluster of galaxies very similar to that Zwicky had found for the Coma Cluster: the large relative motions of thirty individual galaxies, some with velocities of up to 1,500 kilometers per second, would disrupt the cluster unless the average mass for the galaxies was about 200 times larger than the accepted value that had been calculated by Edwin Hubble, based on the amount of light received from these galaxies[3]. Smith even speculated, very presciently, that perhaps the mass estimates for the galaxies themselves were correct but that the unseen mass was likely "internebular material, either uniformly distributed or in the form of great clouds of low luminosity surrounding the nebulae" (that is, material outside of but in between the galaxies).

In 1959, Fritz Kahn and Lodewijk Woltjer, working at the Institute for Advanced Study in Princeton. New Jersey, concluded from a study of our Local Group of galaxies, which includes the Milky Way and Andromeda, that "the Local Group of galaxies can be dynamically stable only if it contains an appreciable amount of intergalactic matter." They speculated further, along the same lines of thought as Smith, that most of that invisible mass might be contained in very hot gas filling up the space in between the galaxies. They were right.

Hot dark matter

Eventually, some of the matter that Zwicky knew must be present was found, but it was not cold and dark; it turns out to be very hot and extremely luminous, and you must have the right tool kind of tools and telescopes in order to see it. The right tools and telescopes happen to be X-ray detectors on X-ray optimized telescopes, which only exist as satellite telescopes since the atmosphere of the Earth, fortunately for all the creatures living on or near the surface of the Earth, stops all X-rays from astrophysical sources from penetrating the atmosphere and reaching the surface.

Beginning with measurements made by sounding rockets in the mid-1960s, projects led by the efforts of Riccardo Giacconi, who was awarded the 2002 Nobel prize in physics for his decades of effort in laying the foundations of X-ray astronomy, galaxy clusters stood out as the brightest astrophysical sources of X-rays. But while the sounding rockets could detect the X-rays, they had a very limited ability to pinpoint where the X-rays came from. Were they from one or more of the galaxies in the galaxy clusters, and/or from the apparent voids in between the galaxies? With the launch of the first X-ray satellites in the early 1970s, astronomers gained confidence in saying that the X-rays from galaxy clusters emerged from clouds of hot gas that exist in the enormous spaces in between the galaxies and not from within the galaxies themselves; finally, with the launch of the

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[3] Modern corrections have reduced the estimate for the overabundance of unseen mass to a factor of 25 or 30.

Einstein Observatory in 1978 and more recently the Chandra X-ray Observatory in 1999, actual images of galaxy clusters taken in X-rays revealed that the spaces in between the galaxies in virtually all clusters of galaxies are filled with clouds of gas at temperatures of tens of millions of degrees. At such high temperatures, the intergalactic gas clouds cocooned within galaxy clusters are prolific emitter of X-rays.

The X-ray emitting gas is clearly hot, in the sense of moving at speeds of a few thousand kilometers per second. At such high speeds, the gravity of an individual galaxy cannot contain the gas. The total mass of the cluster of galaxies, however, can and does contain the X-ray emitting gas. Thus, were this gas truly dark matter, it would qualify as cold dark matter, despite its high temperature. However, this particular kind of matter is not strictly dark, since it emits copious amounts of X-rays.

The total mass made up by hot, X-ray emitting atoms that fill the intergalactic spaces within clusters of galaxies is about ten times greater than the total amount of mass that previously had been identified in the form of stars or clouds of gas inside the galaxies themselves. This is an incredible amount of previously unseen matter. No one, prior to the actual discovery of these intra-galactic cluster gas clouds, would ever have guessed that ninety percent of the mass in clusters of galaxies exists outside of galaxies in the form of hot gas!

Nevertheless, even this hot, bright X-ray emitting gas is not enough mass to solve the dynamical problem first identified by Zwicky. To solve Zwicky's dark matter problem, we need to find matter that is fifty times more massive than all the visible matter in galaxies; the hot intra-galactic gas only provides ten times the mass of the visible matter in galaxies. Some additional matter component, thirty to forty times greater than the mass of the visible matter in galaxies (and, thus, three to five times as massive as the total mass in X-ray luminous matter) and not evident in any studies yet done in any kind of light, not in ultraviolet, visible, or infrared light nor in radio waves or from X-ray telescopic studies, must also be present in these galaxy clusters. Based on some additional evidence, we know that this additional matter must actually be cold and dark.

Kepler's third law

We need a picture in our mind's eye of spiral galaxies like the Milky Way. Spirals are composed of two main components, the disk and the halo.

The luminous disk, which is a flattened structure that contains young and old stars, giant clouds of gas and dust, and large volumes of low-density interstellar medium, extends about 100,000 light years from end to end. The disk of a spiral galaxy extends beyond the visible disk of stars in the form of large clouds of hydrogen gas that can be seen with radio telescopes. Within the disk, the stars and giant clouds generally orbit the galactic center in the same direction.

The visible halo is ellipsoidal in shape, encloses the disk, and is comparable in size to the disk; however, in contrast to the stars and clouds in the disk, halo stars orbit the galactic center in all directions.

Thanks to the work of Johannes Kepler, we can use orbits of celestial bodies to determine how much mass exists in an orbiting system. This is known as Kepler’s third law. Kepler, in 1609, had discovered that the square of the orbital period (designated as ‘P’) around the Sun for every planet was equal to the cube of the size of its orbit (measured as the semi-major axis[4] of their elliptical orbits, designated as ‘a’), that is $P^2 = a^3$. Thus, since we know the orbital period of the Earth (P = 1 year), we can use Kepler’s third law to calculate the size of Earth’s orbit.

Three quarters of a century after Kepler wrote down his third law, Isaac Newton showed that Kepler's third law can be derived mathematically directly from Newton's law of gravity, which explicitly includes the masses of the two orbiting objects and a constant of proportionality known as Newton's gravitational constant. More correctly understood, Newton’s law of gravity reveals that the orbital period of Earth is determined by the total amount of mass *inside Earth’s orbit*. And since 99.9997% of the mass inside Earth’s orbit is contained in the Sun, we can effectively use Kepler’s third law to deduce the mass of the Sun.

The power of Newton's version of Kepler's third law is that if we already know the orbital period and the orbital size for two stars in orbit around each other, we can use those measured parameters for such a binary star system to calculate the only other unknown: the sum of the masses of the two stars. This is an amazing piece of physics. Simply by measuring how long two stars take to orbit each other and the size of those stars’ shared orbit (which we can figure out by measuring how far away the binary system is from us and the angular separation of the two stars), we can measure the total amount of mass of the two stars (though not the masses of either one of the two individual stars, just the sum of their masses).

With the help of Newton's version of Kepler's third law, astronomers can also use the orbital velocities of stars and gas clouds in the disks of spiral galaxies to learn about the masses of galaxies. First, they measure the velocities of stars or clouds in orbit around the center of a galaxy. For a single star or cloud, the velocity, combined with the distance of the star or cloud from the galactic center, immediately yields the orbital period around the center of the galaxy for that object. The orbital period and the size of the orbit, when combined with Kepler's third law, directly gives us the total mass *inside the orbit*.

If a planet were orbiting a double star system, the sum of the masses of both central stars would control that planet's orbit. Now imagine a star that is surrounded by a spherical cloud the size of Jupiter’s orbit containing tens of millions of asteroids. The cloud of

[4] An ellipse is like a squashed circle, and so has a long axis and a short axis, whereas a circle has a radius. Half of the long axis is known as the semi-major axis.

asteroids would have as much mass as the star. Now imagine a planet in orbit around this star that lies a distance ten times greater than the distance of Jupiter from the star, i.e., far outside of the asteroid cloud. In this case, the orbital velocity of the planet would be controlled by the sum of the masses of the star and the asteroid cloud. The fact that the cloud is not compact and is not at or near the center of the orbit does not matter; the fact that the asteroid cloud is spherical and extends as far above and below the plane of the planet's orbit as it extends radially outwards in the plane of the planet's orbit does not matter. The facts that we do not know the sizes of any of the individual asteroids or even how many asteroids are in the cloud do not matter.

Now, let's put the planet in orbit in a different place. This time, we place the planet well *inside* the distance of Jupiter, far inside the outer edge of the asteroid cloud. In this location, the orbital velocity of the planet is controlled by the mass of the central star plus the total mass of asteroids *inside the orbit of the planet*. Even if fifty or ninety-five percent of the asteroids are in orbits outside of the orbit of our planet, their collected mass does not affect the orbital velocity of our planet.

Rotation curves of galaxies: cold dark matter

In 1939, Horace Babcock took advantage of these mathematical and physical properties of gravity and orbits to measure the orbital velocities of stars in the Andromeda galaxy in order to determine how the mass of Andromeda is distributed and, thereby, to attempt to estimate the total mass of the galaxy. Babcock's measurements of the motion of each star in his sample provided an estimate of the mass of Andromeda in the volume of space of the galaxy out to the distance of that star. If most of the mass of Andromeda were near the center, then stars at both intermediate and large distances from the center would have orbital velocities determined by the same amount of mass. In such a case, the orbital velocities would decrease as the distances of stars from the center of the galaxy increases, similarly to how the orbital velocities of planets decrease with distance from the Sun. Astronomers call such a pattern of orbits, found in an environment in which virtually all the mass is near the center, 'Keplerian.'

The Earth, for example, has an orbital velocity of about 30 kilometers per second; the orbital velocity of Jupiter, which is just a bit more than five times further from the Sun than the Earth, is a bit less than two-and-a-half times smaller, at 13 kilometers per second, not the same as Earth's and not five times smaller than Earth's; Neptune is located about 30 times further from the Sun than Earth and has an orbital velocity of about 5.5 kilometers per second, which happens to be about five-and-a-half times smaller. In mathematical terms, when all the mass is concentrated at the center, orbital velocities should decrease in proportion to the square root of the size of the orbit[5].

On the other hand, if the mass of Andromeda is distributed widely throughout the entire

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[5] For example, a planet in an orbit nine times larger than the orbit of the Earth would have an orbital velocity three times smaller.

galaxy, a star at a large distance from the center will be affected by more mass than a star located closer to the center. In this latter case, stellar orbital velocities could increase, stay the same, or decrease slowly as the distances of stars from the center increases.

Measurements of orbital velocities at many distances from the center of those orbits together yield a profile of the distribution of the mass in that system. These plots are known as *rotation curves*. For galaxies, these plots depict the distances of stars from the center of a galaxy on the x axis and the orbital velocities of those stars on the y axis.

What did Babcock discover? Is all the mass in Andromeda near the center, as it is in the solar system, or is the mass distributed uniformly throughout the galaxy? Babcock's results show that the orbital velocities of stars increase from the galactic center out to a distance of about 300 light years. These measurements tell us that the mass within 300 light years of the center is not concentrated near the center; instead, the amount of mass steadily increases as we move outwards to a distance of 300 light years. Moving further out, orbital velocities decrease out to about 1,000 light years. This part of the rotation curve is nearly Keplerian, and suggests that most of the mass with l,000 light years is actually concentrated within 300 light years of the center. Not much mass is added in between 300 light years and 1,000 light years. However, from 1,000 light years all the way out to about 20,000 light years from the center, *the stellar velocities steadily increase*. This result is only possible if the mass of Andromeda is distributed throughout the galaxy from distances of 1,000 light years out to 20,000 light years, with vast amounts of mass found at great distances from the center.

Prior to Babcock's work, the mass of Andromeda had been estimated in a different way, from the total light emitted by all the stars and clouds of gas and dust observable within the galaxy. The mass distribution inferred from using light to identify where the stars and clouds were located and how much light they produced indicated that a great deal of mass was near the center of the galaxy, with some but much smaller amounts of mass in the outer parts of the disk. Such a mass distribution should have looked nearly Keplerian, with stellar and cloud velocities decreasing slowly but steadily with increasing distance from the center. This, of course, is not what Babcock found. Instead, the mass estimated from the light emitted by the galaxy vastly underestimated the amount of mass estimated from the orbital velocities.

If the velocities of the stars are greater than expected, as predicted from the amount of mass inferred from other measurements to be present in the galaxy, then *additional mass must be present that is unseen*. That invisible matter must be *inside the galaxy*. Since this matter has not evaporated from the galaxy, it must be moving at speeds comparable to the speeds of the stars, not comparable to the speed of light, and so it must be cold as well as dark.

In 1962 Vera Rubin took up where Horace Babcock had left off. Rubin measured the orbital velocities of 888 stars located in the Milky Way, all within distances of 10,000 light years of the Sun, in order to determine the rotation curve for the Milky Way at distances from 16,000 light years to 36,000 light years from the center of the galaxy. Like Babcock had found for Andromeda, Rubin found that "for R > 8.5 kpc [beyond 8,500 parsecs (28,000 light years), which is further from the center of the galaxy than the Sun], the stellar curve is flat, and does not decrease as expected for Keplerian orbits." Such a flat rotation curve can be generated if the amount of mass in the galaxy, at distances from 25,000 to 35,000 light years from the center, increases with distance from the center at the same rate as the distance increases (that is, mass is directly proportional to distance).

Flat. Another word entered the lexicon of modern astronomy. Flat rotation curves for galaxies indicate that stars have essentially the same orbital velocities across a vast range of distances from the center. Since the luminous mass in galaxies is insufficient to provide the gravitational force necessary to generate the observed orbital velocities, the only way to generate flat rotation curves is for galaxies to have enormous amounts of mass that is cold and dark, mass that is trapped inside the galaxy and distributed widely throughout the galaxy. By the mid-1970s, a cottage industry had developed in which astronomers measured rotation curves of spiral galaxies and, without exception, found the same answer: they were all flat.

While by the mid-1980s the evidence for the existence of dark matter had become overwhelming, the nature of the invisible matter, however, remained a cold, dark secret. From the previous two hundred years of finding evidence for unseen matter, astronomers had learned that dark matter, once found and identified, always turns out to be objects (black holes, white dwarfs, planets, hot gas) made out of the same kind of matter found on Earth. The next step, then, was to design observing projects that would reveal the dark but presumably common nature of the cold dark matter responsible for the flat rotation curves of galaxies.

In order to explain the flat rotation curves of spiral galaxies, some of the dark matter must be cold dark matter, confined within galaxies. Perhaps the cold dark matter is composed of lots of comets and Jupiter-sized objects floating between the stars. Perhaps the cold dark matter component of the mass of the galaxy is dominated by faint red stars or white dwarfs or neutron stars or black holes. None of these choices are likely, however, as observations already made by astronomers place upper limits on how much mass might exist in the form of these kinds of unseen objects. Alternatively, the cold dark matter might be composed of enormous numbers of small particles, some slow moving (cold), others fast moving (hot), that are hard to find and identify but are nevertheless out there, filling up the galactic and intergalactic space. Another observing technique would reveal the answer.

Gravitational lensing

If I were to travel from New York City to Beijing, I could save money on fuel if I chose to travel the shortest physical distance between the two cities. The very shortest path imaginable connecting New York City and Beijing through the three dimensions of space with which we are familiar would be through a straight-line tunnel carved through the crust and mantle of the Earth. Such a long deep tunnel to China, of course, does not now and is unlikely to ever exist. The shortest path that is actually possible would be by air, skimming just over the Earth's surface and going over the North Pole. Since our flight path would be located only a few thousand feet above the Earth's surface, the line marking out my shortest path effectively would be drawn on the curved surface of the Earth. In the language of mathematics, my flight path would be known as a geodesic, the absolute shortest possible path that connects two locations through the curved space (in this case, the curved surface of Earth) through which we can actually travel.

One of the more mundane aspects of the physics of light is that light travels along the shortest possible path through space from point A to point B. Since space, like the surface of the Earth, is curved, that shortest possible path may not look to us like a straight line through flat space. One of the more dramatic predictions that emerged from Einstein's theory of general relativity, which is fundamentally a mathematical description of gravity, is that mass determines the shape of space. Specifically, in the presence of small amounts of mass space appears to be very flat while in the presence of large amounts of mass space is measurably curved. Light cannot travel outside of space so light will travel along the shortest available path through curved space. We could reasonably describe the light path as a straight line (i.e., the shortest path) through curved space. This is not, however, the language we normally use. Instead, we talk about mass bending the path of light, which makes the phenomenon sound, incorrectly, as if the light is traveling along curved lines through flat space. But no matter how we describe this phenomenon, the result is the same: light travels along the shortest possible path, the quickest route, through space that is sculpted by mass.

Sir Arthur Eddington famously led an expedition in 1919 to observe starlight passing near the Sun during a total eclipse of the Sun, as an experimental test of Einstein's theory of general relativity. The idea was straightforward: during the eclipse, Eddington and his team attempted to detect rays of light from some stars in the Hyades star cluster, which was located near the limb of the Sun during the five-minute eclipse on May 29. Since Einstein's theory predicts that the mass of the Sun curves space so that the space near the Sun acts like a lens to bend and focus light, these stars should be displaced outward from their expected locations, were the Sun not nearly in between Earth and those stars. The Eddington expedition was a success; in London on November 6, the Astronomer Royal, Sir Frank Dyson, reported the eclipse results to professional colleagues at a closed meeting of the Royal Society and the Royal Astronomical Society. On November 7, *The Times* of London, under a banner headline "Revolution in Science, Newtonian Ideas Overthrown," reported that "The scientific concept of the fabric of the Universe must be changed." Three days later, the *New York Times* offered the headline "Einstein Theory Triumphs, Stars Not Where They Seemed or Were Calculated to be." Einstein became world famous overnight.

In recent decades, astronomers have observed numerous examples of massive objects bending light. This phenomenon is now called *gravitational lensing* and the massive object bending light is called a *gravitational lens*. Gravitational lenses that have been discovered in recent years include Earth-sized planets orbiting distant stars in the Milky Way as well as supermassive galaxy clusters in the relatively distant universe. The exact number and shape of the distorted and lensed background sources depend on several factors, including the mass of the gravitational lens, the distance from Earth to the gravitational lens, the angle from the lensing to the lensed object, and the distance from the gravitational lens to the even more distant background object whose light is lensed. If the mass of the gravitational lens is large enough and the angle between the lensing object and background object is small enough, we will see multiple images or a stretched out and curved image of the background object. This situation is known as strong gravitational lensing. In other cases, the lens is not strong enough to generate multiple images or a stretched and curved image of a single background source but is strong enough to distort (stretch) the shape of the lensed object. This situation is known as weak gravitational lensing.

The Bullet Cluster

One very special place where the gravitational lensing technique has been applied is the Bullet Cluster. The Bullet Cluster actually consists of two clusters of galaxies that collided at a relative speed of 4,500 kilometers per second, which is about 1.5 percent of the speed of light. In thinking about the collision, we need to consider what should happen to the main components of the Bullet Cluster during the collision. One component is comprised of the constituents of every galaxy that generate substantial amounts of visible, infrared, and radio light. These are the stars and clouds of gas *within* every galaxy in each of the two galaxy clusters; they are made of normal matter. The second component is the million-degree *intergalactic* gas, most of which is hydrogen, that we know can be seen in X-rays and which is also made of normal matter. The third component is the dark matter that we know comprises as much as eighty percent of the mass that is *inside* of every galaxy, though we do not know what that dark matter is made of.

Remember that the physical sizes of the visible parts of galaxies are a few tens of thousands of light years across (the visible part of the Milky Way has a diameter of about 100,000 light years), which are very small in comparison to the millions-of-light-year distances between galaxies within a cluster (the distance from the Milky Way to Andromeda is about 2.5 million light years). Similarly, the wingspan of a single goose in a flying flock of geese is typically much smaller than the separation between the wing tips of any two geese.

Now imagine that two flocks of geese are flying in opposite directions over the Willis Tower (formerly the Sears Tower) in downtown Chicago. In such a situation, no two geese are likely to collide; the two flocks pass right through each other with nary a bump or a honk.

Next imagine that one of our flocks of geese is migrating northward from Florida toward Canada. Because of a high-pressure system in the Gulf of Mexico, hot moist air from the Gulf is being pushed northwards with the flock of geese at the same speed and in the same direction as the geese are flying. In effect, the geese are embedded within a large bubble of hot, moist air and both the geese and the bubble of hot air are traveling northwards together.

Meanwhile, our other flock is over Canada headed southbound to Florida, but because of a high-pressure system in the Arctic that is pushing cold air to the south, these geese are embedded within a large bubble of cold Arctic air and are flying southwards at the same speed and in the same direction at which the cold front is moving to the south. In effect, each 'flock' consists of two kinds of matter: animate matter, consisting of a few hundred geese, and a bubble of inanimate matter, consisting of countless, invisible air molecules.

Again, let's imagine that the two 'flocks' meet over the Willis Tower. Again, the geese fly right past each other, but when the bubbles of hot and cold air pass over the Willis Tower at the same time as the geese, the air bubbles collide violently. They are unable to pass through each other so, after smashing into each other, they come to rest. Now a weather front is suspended over Chicago. The crash of thunder and the flash of lighting fill the sky over the Willis Tower. Despite the collision of the air bubbles, which has stopped the hot and cold air parcels over Chicago, the geese keep on flying, one flock onwards to Canada and the other onwards to Florida. In a few hours, one flock of geese is already far north of Chicago, winging its way further northward over Wisconsin, while the other is already far south of Chicago, flying over Indiana as it continues its southward migration. Meanwhile rain falls on Chicago.

The visible galaxies in the two clusters, like the geese in our two flocks, sail right past each other, with each galaxy barely noticing the presence of any other galaxies. The galaxies do interact through the force of gravity, so they pull on each other a little bit. Some might even be distorted or stretched by these gravitational interactions, but the galaxies are so far apart and moving past each other so fast, that the gravitational tugs are too small to have any immediate or long-term effects on the galaxies.

But remember that each cluster of galaxies is filled with a cloud of million-degree gas that fills up the entire volume of space between the galaxies in each cluster. When the clusters try to pass through each other, the clouds of million-degree gas smash into each other, like a hot front meeting a cold front in the atmosphere of the Earth. As a result of the head-on collision of the two gas clouds, the two clouds are stopped in their tracks while the galaxies themselves keep on going in the directions in which they were originally moving. Today, long after the galaxy clusters first collided, the X-ray bright gas clouds have been left behind at the sight of the collision while the visible galaxies have continued in the directions in which they originally were moving.

Now, our understanding of the Bullet Cluster gets interesting. Remember that in a typical galaxy cluster, the total mass of gas evident as hot, intergalactic, X-ray emitting plasma is ten times greater than the amount of mass generating the visible, infrared, and radio light from the stars and cold gas clouds in the galaxies. The Bullet Cluster is no exception: the X-ray emitting plasma, which has now been removed from both clusters of galaxies, contains about ten times more mass than the total mass of the stars and gas clouds in the galaxies. Now, many years after the collision, the Bullet Cluster consists of three main regions. The central region, revealed in the hot gas seen in Chandra X-ray Telescope images, contains about ninety percent of the ordinary matter; the two clusters of galaxies, one on each side of the hot gas region and revealed in Hubble Space Telescope images, together contain about ten percent of the ordinary matter.

Given this distribution of mass, if the Bullet Cluster were to act as a gravitational lens of more distant galaxies, the volume of space containing the greatest amount of mass should act as the dominant gravitational lens, and since the X-ray emitting gas contains ten times as much mass as the visible galaxy clusters, *the hot gas cloud should serve as the center of the lensing environment. Amazingly, observations reveal that the opposite situation occurs*.

In 2004, Douglas Clowe, then at the Steward Observatory in Arizona, led a team that used the Hubble Space Telescope to study the weak gravitational lensing effects of the Bullet Cluster. They found that the region *associated with the visible galaxies* is responsible for the gravitational lensing. In fact, about 80 percent of the total mass of the Bullet Cluster is associated with the region of space where the visible clusters of galaxies are located; yet the X-ray emitting plasma contains ten times more mass than the normal matter producing the light we see when we observe the galaxy clusters. The only viable explanation is that an enormous amount of dark matter still surrounds the galaxies within the clusters. Furthermore, whatever this dark matter is, it interacts gravitationally but is otherwise effectively collisionless: when the galaxy clusters collided, *the dark matter components passed right through each other*, as did the visible galaxies.

The observations of the Bullet Cluster tell us that we need to think of a galaxy cluster as containing three mass components. The first, which provides at most one to two percent of the mass of the cluster, is the normal matter that makes up the stars and clouds of gas that light up the galaxies. The second, which accounts for ten times more mass than the first, i.e., perhaps 10 to 20 percent of the total cluster mass, is also composed of normal matter in the form of hot intracluster gas that emits copious amounts of X-rays. *The third, which accounts for 80 to 90 percent of all the mass in the cluster, is the cold dark matter that surrounds and permeates each visible galaxy. And what makes up all the cold dark matter? We still do not know*.

In 2008, a team lead by Maruša Bradač, of UC Santa Barbara, studied another massive merging galaxy cluster and found another cluster that yielded the same results as the Bullet Cluster: the stars (the visible galaxies) comprise about one percent of the mass of the colliding galaxy cluster system, the mass in intergalactic gas makes up about nine percent of the total mass, while *collisionless dark matter makes up the remaining 90 percent*.

The two 'bullet clusters' provide extremely powerful visual evidence for the presence of all three of these distinct components including, most importantly, enormous amounts of cold dark matter that does not collide with or otherwise interact with the normal matter. In fact, the collisionless cold dark matter is by far the dominant component, by mass, of these two merging or colliding galaxy clusters. We just don't know what the cold dark matter is.

The case for dark matter

A century ago ago, dark matter had a well understood meaning to astronomers: matter that produces so little light that it was hard to see. But as astronomers' tools improved, much of that not-too-luminous matter, whether found as hot gas in disks around black holes or as white dwarfs or distant planets or faint stars or hot intergalactic gas, became visible. Now, dark matter is defined a bit differently.

Dark matter, in modern terminology, includes normal matter (composed primarily of protons, neutrons, and electrons)[6] that exists in forms that make it hard or impossible to see. Such objects include black holes, neutron stars, white dwarfs, and hot intergalactic gas. Dark matter also includes matter that affects other objects through the force of gravity but does not interact with other objects in any other way (or interacts so weakly that the non-gravitational interactions are negligible compared to the gravitational interaction). Such objects would be composed of non-baryonic dark matter, but we have no idea what that matter is composed of.

The evidence for the existence of non-baryonic dark matter with these qualities is now overwhelming, including the too-fast motions of galaxies in clusters of galaxies, the too-fast orbital velocities of stars and gas clouds in spiral galaxies, the gravitational lensing seen toward colliding galaxy clusters, the impossibility (according to theoretical calculations) of forming galaxies at all unless the gravitational influence of non-baryonic dark matter triggered the process.

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[6] Physicists call this kind of matter baryonic dark matter.