# WHAT'S THE MATTER?

## Exploring the invisible majority of the universe's mass

by Andrew Wetzel

Forget Pluto. While its demotion to a "dwarf planet" had many up in arms, the most exciting news from astrophysics last fall came from well outside our solar system. The observation of a collision of two clusters of galaxies, one of the most energetic events since the Big Bang, has provided a key to one of the most outstanding problems in astrophysics today: dark matter.

Looking at the sky on a clear, dark night, your gaze encompasses light from more than 100 billion stars. With the aid of a modern telescope, you could see again as many galaxies. Even though this would amount to over one sextillion stars (that's 1,000,000,000,000,000,000,000!), all the visible light you see comes from less than 20 percent of the total matter in our universe. The rest is thought to exist in a mysterious invisible variety that cannot be directly detected by conventional means and is unlike anything we have ever seen. Not stars, not planets, not asteroids, this "dark matter" is necessary to account for the strong gravitational interactions of stars and galaxies observed by astrophysicists, which cannot be explained by ordinary matter alone.

Over the past 30 years, UC Berkeley astrophysicists have led the way in studying dark matter and its effects on the universe. Until recently, they have had to piece together evidence for the existence of dark matter indirectly. Last fall, however, a stunning observation of the "Bullet" galaxy cluster provided direct evidence of dark matter, further solidifying our model of the universe and making alternative theories all but obsolete.

**A brief history of dark matter**

The idea that some form of dark matter pervades our universe is not new. It was first introduced in 1933 by the Swiss astrophysicist Fritz Zwicky, who studied the Coma cluster of galaxies, a gravitationally bound cluster of over 1,000 galaxies located 300 million light-years away. Zwicky was able to measure the velocities of galaxies as they swirled around in the cluster. Since the pull of gravity is responsible for the galaxies' motions, he could estimate the total gravitational mass in the cluster based on these velocities. Zwicky compared the cluster's mass from the velocity measurements with another calculation of the mass obtained by measuring the summed brightness of all the galaxies. Remarkably, his velocity-based calculations suggested that there was 400 times more mass in the cluster than the brightness-based estimate. With uncanny foresight, Zwicky concluded that some form of "dark" matter was providing the extra gravity needed to reconcile the two measurements and explain the rapid galactic dynamics.

For nearly 40 years, Zwicky's observation of the Coma cluster remained the only piece of evidence for dark matter. However, in the early 1970s, the astrophysicist Vera Rubin stumbled upon an equally surprising discovery. According to standard Newtonian theory, stars orbiting inside galaxies should behave the same as planets orbiting our sun; the closer an object (like a planet) is to the central gravitational source (the sun), the more gravity it feels, and the faster it orbits. Conversely, the farther the orbiting object is from the central mass, the slower its orbital velocity will be. However, Rubin observed that the stars in the outer regions of spiral galaxies orbit with the same rotational velocity regardless of their distance from the galaxy center, a result in stark contrast with the expectations of ordinary Newtonian gravity. Since Rubin's results held true for a host of different observed galaxies, the conventional physical theories had reached a breaking point. Astrophysicists were forced to either modify the rules of gravity or accept that a galaxy's mass might include invisible material. In conjunction with Zwicky's similar findings on the Coma cluster, the latter modification seemed more probable. Astrophysicists begrudgingly began to accept that galaxies live in much larger halos of dark matter, and thus most of the matter in our universe is invisible.

As astronomical observations improved, knowledge of dark matter's properties became more sophisticated. One of the early pioneers in dark matter and its effect on the formation of galaxies and galaxy clusters was UC Berkeley Professor of Astronomy and Physics Marc Davis. Davis was one of the first scientists to hear about Rubin's results on

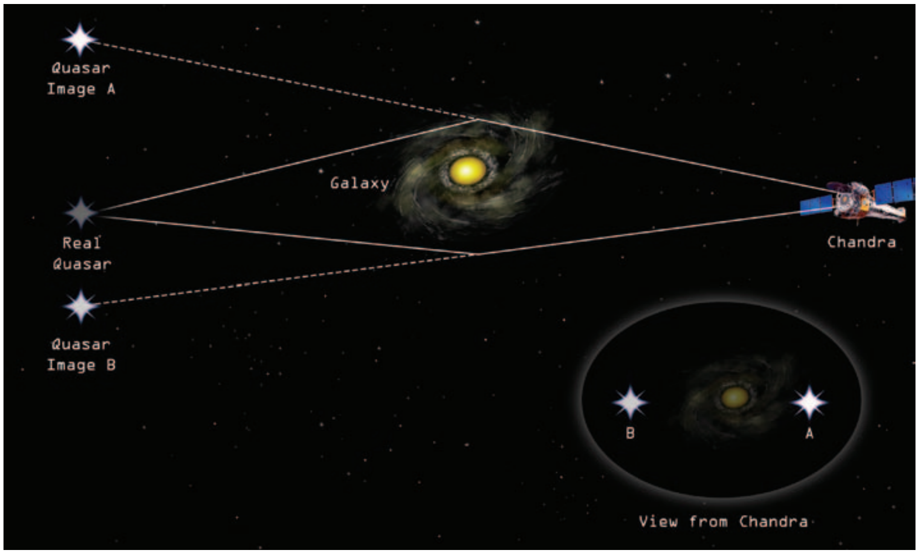


*Image courtesy of NASA/CXC*

(left) As light from a distant source passes by a massive object like a galaxy, the curvature of space from gravity bends the trajectory of the light, much like a lens does. In severe cases, this gravitational lensing can cause a single distant object to appear as two. (below) These stills show four stages from an artist's representation of the Bullet cluster collision. Hot gas, containing most of the normal matter in the cluster, is in red and dark matter in blue. As the galaxy clusters collide, the dark matter moves unimpeded while the gas lags behind. The resulting misalignment of the dark and normal matter can be seen in the real images of the cluster.

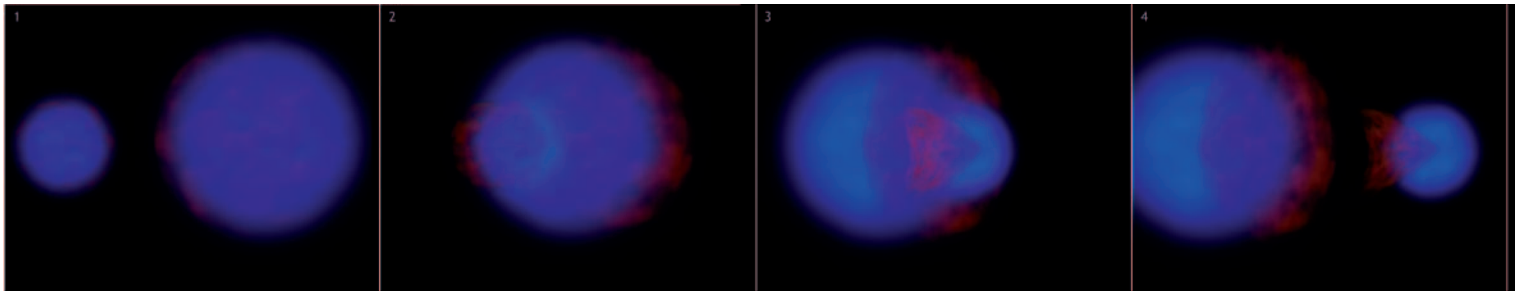

*Image courtesy of NASA/CXC/M. Weiss*

galaxy rotation curves. "As a graduate student, I spent some time at the Lowell Observatory in Arizona. While there, I met Vera Rubin over dinner one night. She told me about her results, and this was before she had published them." With a look of wonder that belies his now profound knowledge, Davis recalls, "I was mystified."

During the 1970s, Davis began an ambitious observational survey to map the positions and distances of the 2,000 brightest galaxies in the northern hemisphere to study how matter is distributed within our universe. "Back then, it was a state of fractured knowledge. There was not much thought of studying the universe as a whole, and little was known about the large-scale structure (beyond the scale of galaxies) of our universe. People were mainly interested in observing and finding the distances to specific 'interesting objects.' We had no feel for the overall picture of dark matter until large-scale survey maps."

Following this work, Davis moved to UC Berkeley in 1981 to work on dark matter theory. Davis and his group were the first astrophysicists to use supercomputer simulations to model how galaxies cluster and form. Through these simulations, he found that he needed to invoke dark matter to explain how galaxies were able to form as fast as they did. "The data we found in our observational surveys were not matching our simulations of galaxy interactions. So we started thinking about dark matter, and we realized that it was needed to explain the structure of our universe."

## The search for dark matter

With the mounting evidence from Zwicky, Rubin, Davis, and others, the astrophysical community began to accept that dark matter provided a natural explanation for a number of cosmic mysteries. However, the exact composition of dark matter remained mysterious. Physicists understood everyday matter, including the protons, neutrons, and electrons that comprise the atoms inside our bodies. Could dark matter particles be some variation of ordinary matter? And could they be hiding unseen in the form of dead stars that no longer shine? Referred to as Massive Compact Halo Objects (MACHOs), dark matter was long thought to exist in the form of failed stars known as brown dwarfs, super-dense dead stars known as neutron stars, or infinitely dense collapsed stars called black holes. However, such highly massive objects would leave distinct gravitational footprints that astrophysicists could observe within our galaxy. Despite years of searching, astrophysicists have not been able to find enough of these objects to account for the effects of dark matter, leaving MACHOs an untenable explanation.

If dark matter cannot be explained by highly massive clumps of "normal" particles, then perhaps it lies in particles quite unlike those that physicists have observed. As if to reinforce their radical departure from MACHOs, physicists affectionately called these candidate objects Weakly Interacting Massive Particles, or WIMPs. Such particles are called "weakly interacting" since they do not emit, absorb, or reflect light. Despite the fact that they may weigh only one quadrillionth an atom, they are thought to be numerous enough in our universe to outweigh atoms by a factor of five to one. Currently, the two most favored particle candidates are called axions and neutralinos, and astrophysicists believe that these particles are diffusely distributed, much like a gas, in the dark matter halos that surround galaxies.

The uncertainty in the composition of dark matter remains problematic to most physicists. "No physicist worth his salt is going to like this until you can actually discover dark matter in the laboratory," says Davis. A number of

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experimentalists have sought to do just that, including Bernard Sadoulet, Professor of Physics at UC Berkeley. He has been working for over two decades to directly detect dark matter particles. His experiments are based on trying to measure the interactions between WIMPs and a highly sensitive target as the WIMPs pass through the earth. However, such measurements are fraught with difficulties, as they rely on the supposition that WIMPs somehow can interact with ordinary matter and that detectors can be precisely tuned to measure such a weak signal. Despite twenty years of pursuit, the elusive particles that make up dark matter have evaded detection.

## Dark matter and cosmology

Despite their lack of understanding of the exact form of dark matter, astrophysicists have been able to learn an impressive amount about it over the last twenty years through a wealth of cosmological observations. Foremost among them have been the measurements of the Cosmic Microwave Background (CMB), light that was emitted after the Big Bang and that fills the universe. By measuring how the temperature of this background radiation (which is mostly in the form of microwaves) changes across the sky, astrophysicists can determine the properties of the universe in its infancy. (This measurement was first performed by UC Berkeley

From top to bottom: (1) The optical image of the Bullet cluster. Note the clump of galaxies in the center. (2) The X-ray image of the hot intercluster gas (red) superimposed on the optical image. A bullet-shaped cloud of gas forms in one of the clusters as a result of the collision. (3) The image of the predominate mass distribution of the cluster (blue), as obtained from measurements of gravitational lensing. (4) Superposition of all three images. Note that the predominate mass distribution (blue) is displaced from the hot gas (red), which contains 90 percent of the ordinary matter in the cluster. The clear separation between the normal matter and the bulk of the mass in the cluster gives direct evidence for the existence of dark matter.

Credits: (1) NASA/STScI; Magellan/U.Arizona/D.Clowe et al. (2) NASA/CXC/CfA/M.Markevitch et al. (3) NASA/STScI; ESO WFI; Magellan/U.Arizona/D.Clowe et al.

Professor and 2006 physics Nobel laureate George Smoot.) These measurements indicate that ordinary matter such as protons, neutrons, and electrons represents only five percent of the total density of the universe. However, five times more gravitational matter is needed to explain the formation of galaxies. If such matter were not around, our own Milky Way galaxy would not yet have formed, despite the universe's 14-billion-year history.

Martin White, UC Berkeley Professor of Physics and Astronomy, has been examining the ramifications of the CMB for over a decade. He first became interested in cosmology as a Berkeley postdoc working on theoretical predictions of the CMB. According to White, "The CMB has provided some of the best constraints on the properties of dark matter."

In addition to the CMB, perhaps the most compelling piece of indirect evidence for dark matter comes from gravitational lensing. According to Einstein's General Theory of Relativity, gravity is actually a curvature of space, not a force. Imagine three-dimensional space as a flat rubber sheet. If you roll a marble across it, the marble moves in a straight line. However, if you put a bowling ball in the middle of the rubber sheet, it will "bend" and the marble's path will curve around the bowling ball. If the marble rolls too close to the bowling ball, it may become trapped in the curvature, thus orbiting around the bowling ball. This analogy explains why the planets orbit around the sun in our solar system.

Since space itself is warping, the paths of *all* objects are affected. Thus, gravity can bend even the path of light, much like a lens does. Astrophysicists see this "gravitational lensing" as they peer deep into the cosmos. By examining the degree to which the light path is bent, astrophysicists can measure how much mass lies between them and the light source. In most cases, there is not enough visible matter between our telescopes and the source to explain the amount of gravitational lensing observed. Through this method, astrophysicists are able to indirectly map the distribution of dark matter in our universe. White, also an expert on the effects of gravitational lensing, contrasts the information gained from the CMB with that of gravitational lensing: "The CMB provides a means of weighing dark matter, while gravitational lensing provides a means for mapping it." Thus, while we may not yet understand what dark matter is, we now have a good understanding of how much exists and where it is.

## Enter the bullet

Most astrophysicists have come to embrace dark matter, despite the indirect nature of the evidence for its existence. While they can observe the gravitational signature that dark matter leaves in its interactions with visible matter, they have yet to directly detect dark matter particles. Last fall, however, astrophysicists were blessed with the next best thing: a stunning observation that provided empirical proof of the existence of dark matter.

In 1995, astrophysicists discovered a massive cluster of galaxies in the southern constellation Carina located 5 billion light-years away. (To give a sense of cosmological scale, our own Milky Way Galaxy is only 100,000 light-years in diameter.) Upon closer inspection, astrophysicists learned that this galaxy cluster was in fact two clusters that had undergone a fantastic and rare collision. With one of the clusters plowing through the other like a shot in the night, the cluster earned the apt nickname, the "Bullet." We see the galaxy clusters separated by two million light-years, as they were 100 million years after their collision.

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Most of the ordinary matter in a galaxy cluster lies not in the galaxies, but rather in diffuse intercluster gas. The Bullet cluster, which has the mass of a quadrillion suns, has enough gravitational energy to heat its interior gas to such high temperatures that the gas radiates high-energy X-rays. Douglas Clowe from the University of Arizona and his colleagues used the space-based Chandra X-Ray Observatory to image this hot intercluster gas. They then used two optical telescopes based in Chile, along with the Hubble Space Telescope, to measure the effects of gravitational lensing. By analyzing the distortion due to gravitational lensing of background galaxies in the field of view of the Bullet cluster, they mapped the cluster's total mass distribution, finding that most of the mass lies in the same regions as the cluster's central galaxies. However, when comparing the location of the hot intercluster gas (which constitutes most of the ordinary matter) with that of the mass derived from gravitational lensing, Clowe and his colleagues found a startling result: The visible matter and gravitational matter are displaced from one another! Thus, most of the mass in the cluster is invisible, yielding direct proof of dark matter.

How did the ordinary matter and dark matter become so misaligned? Thanks to the violent collision, the ordinary matter was swept out of the clusters, displacing it from the dark matter (and galaxies). Unlike dark matter, which does not interact with anything except via gravity, intercluster gas undergoes a drag force, similar to air resistance, when it encounters more gas. So, while the hot gas was busy colliding, the dark matter passed through effortlessly. Because of the observed misalignment, we now know that there is dark matter out there.

The astrophysical community responded to the stunning Bullet cluster result primarily with excitement and satisfaction. For most astrophysicists, who had long ago accepted dark matter, these observations were merely the icing on the cake. White notes that while the Bullet cluster did not yield any quantitatively new results, it was extremely useful, since it was "one system, with a clear indication of what was happening. We did not have to piece together four separate lines of evidence for dark matter."

## The future of dark matter

With the new evidence for dark matter in place, what is the future of research on dark matter?  Most current

## Maybe the MOND theory?

After Vera Rubin's discovery of the anomalous rotation curves of galaxies in the early 1970s, Zwicky's original 1933 hypothesis, that galaxies are embedded in a much larger halo of dark matter, has remained the favored explanation. However, for some physicists, the idea of postulating a new form of matter was too unappetizing. Instead, they wondered if the laws of gravity needed updating. In the early 1980s, Mordechai Milgrom, a physicist based in Israel, did just that. He developed a modification of Newtonian dynamics (MOND) that successfully described the rotation curves of galaxies without the need for dark matter. Under ordinary Newtonian mechanics, the force on an object is proportional to its acceleration. This cornerstone principle of physics has been fantastically successful in describing a wide range of gravitational phenomena, from the speed of a rollercoaster barreling down an inclined track to the motion of planets around our sun. However, Milgrom pointed out that Newton's famous second law has only been tested when the force of gravity is strong. He posited that on the scale of galaxies, where the separation of objects is enormous and hence the force of gravity is comparatively small, Newton's second law could change such that the force is proportional to the *square* of the acceleration. If true, this means that stars far from the galaxy center would rotate faster than expected. As it turns out, such a modified version of gravity, where Newton's law holds when gravity is strong but changes where gravity is weak, is able to beautifully describe the rotation curves of galaxies, without having to invoke a mysterious dark matter.

Unfortunately, MOND falls tragically short in explaining the results of galactic structure formation, galaxy cluster dynamics, and the Cosmic Microwave Background. While MOND advocates are continually updating the theory to try to explain these observations, most physicists are critical of MOND because it can only successfully explain the results of galaxy rotation curves, whereas dark matter is able to explain at least a half dozen disparate phenomena. Davis is quite direct: "MOND is a complete waste of time. . . It is much easier to accept dark matter than to throw out Einstein's gravity." White agrees that "the general theoretical notion of modifying gravity is valuable, since we do not know for certain that Einstein's Relativity is correct on all scales. However, most theorists regard the traditional MOND theory as rubbish."

Perhaps most importantly, the results of the Bullet cluster cannot be explained simply by modifying gravity, since the majority of the mass (derived from gravitational lensing) is displaced from the majority of the visible matter (the hot gas). Even in MOND, the gravitational force would have to point back to its source, from our point of view overlapping with it. Because of the observed misalignment, independent of any model of gravity, we now know that there is dark matter out there.

observations aim to describe even more precisely the astrophysical properties of dark matter. Davis continues his work on large-scale observational surveys of galaxies; he is currently using the Keck telescope in Hawaii, the largest optical telescope in the world, to obtain precise distances of galaxies as far as ten billion light-years away. With these data, he hopes to study the structure of the universe in the earliest days of galaxy formation. As for the big picture, however, White believes that "we have gone essentially as far as we can go astrophysically to constrain the properties of dark matter. We know approximately how much there is, how dark matter traces mass, that dark matter has very limited interactions beyond gravity, and so on. The main thing left is direct particle detection."

However, the question of the source of such a direct detection remains open. Both White and Davis are skeptical of detection arising from traditional dark matter searches, like Sadoulet's underground detectors. According to White, "Most likely, dark matter particle detection will occur at the Large Hadron Collider," the next generation particle accelerator on the France-Switzerland border that is set to begin operations later this year. Such accelerators crash fundamental particles into one another at high enough energies to create new particles, and perhaps a dark matter particle could be one of those created and detected in such a highly controlled environment. Davis, meanwhile, remains optimistic of astrophysical detections: "I vote that dark matter particles will be seen in decay processes in the galactic center, where the density of dark matter is highest." Davis's intuition could be true if dark matter particles somehow decay and emit high-energy light rays, a process theoretically proposed to exist, but yet to be experimentally verified.

While the search for dark matter has left a number of physicists frustrated, others view it as an exciting opportunity to expand our knowledge of the universe. Indeed, dark matter is perhaps the most compelling evidence for the existence of new kinds of particles outside the accepted roster of fundamental particles in the universe. As a result, the investigation of dark matter, unlike Pluto, has a bright future ahead. ■

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*Want to know more?*

Martin White's website on dark matter:
`astro.berkeley.edu/~mwhite/darkmatter/dm.html`

NASA's Chandra X-Ray Observatory: `chandra.nasa.gov`