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Invisible Galaxies: The Story of Dark Matter

By Matthew Craig and Sara Schultz

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Introduction

Sometimes astronomers need a reality check. The other evening I was talking to my mother about dark matter[1], and the more I said, the more she looked at me like I was nuts. It started when she asked me about my summer plans. The plans involve dark matter, so the question "What is dark matter?"[2] arose almost immediately.

I explained that dark matter is this stuff that you cannot see, touch, taste, hear or feel, even with the most sensitive instruments. She looked suspicious. I added that most of the matter in the universe is dark matter[3]. She looked more suspicious. Getting a little desperate I confidently said the stuff is everywhere, even in our galaxy. Her face said she thought I was off my rocker. Out loud she asked, "How do you know this stuff really exists if you can't see it? Especially if there is so much of it!"?

I realized then how poorly everyday life prepares one for understanding what the universe is made of. The Earth is a really exceptional place. Think about the kinds of things you encounter each day. You breathe air, which is mostly nitrogen and oxygen. You drink water, which is mostly oxygen by weight with some hydrogen. You eat food containing sugars composed of carbon, hydrogen and oxygen. The ground you walk on is composed of relatively heavy elements like silicon, iron and oxygen. It is natural enough to conclude the whole universe must be like this, a lot of heavy elements, a bit of hydrogen, and essentially no helium.

In this image, dark matter (shown

It is not.

The things you breathe, eat, and drink on Earth make up less than 1% of the sun. A star, like our sun, is about 75% hydrogen and 24% helium. Every object larger than a planet that we see in the universe is pretty similar to the sun in terms of its composition: mostly hydrogen, some helium, not much else.

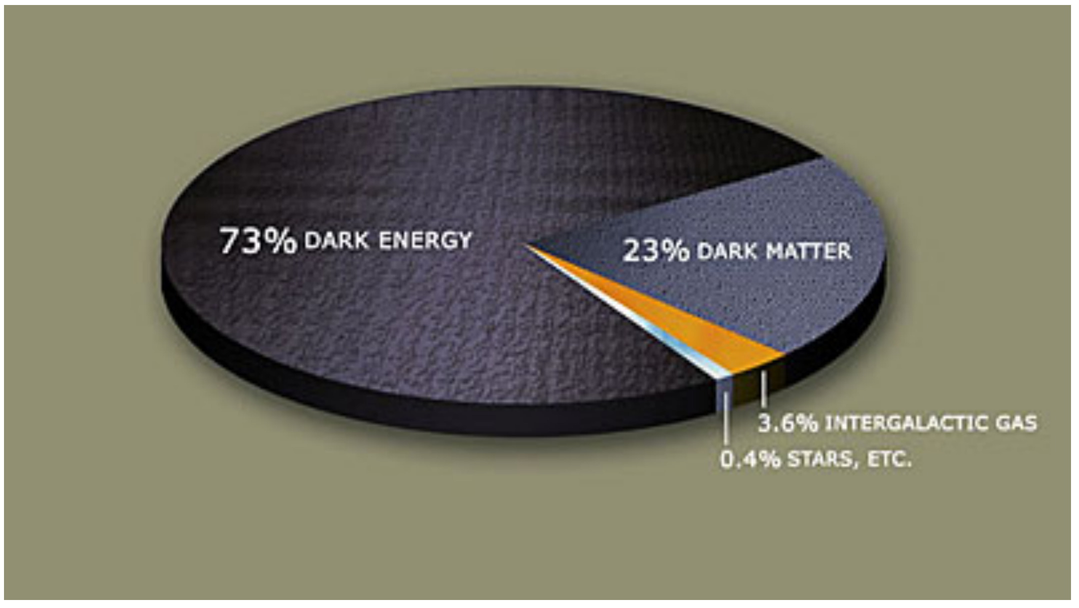
in blue) has become separated from luminous matter (shown in red) in the bullet cluster.

Image credit: X-ray: NASA/CXC/CfA/M.Markevitch et al.; Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.; Lensing Map: NASA/STScI; ESO WFI; Magellan/U.Arizona/D.Clowe et al

So what about this dark matter stuff? Mom thought I was trying to change the subject so she gently reminded me to get to the point.

The point is that just as the materials commonly found on Earth don't represent what you observe in the sun, the materials that comprise the Sun don't represent all the matter there is in the universe. When you look at a galaxy the stuff that you see with a telescope is only a relatively small fraction of the stuff that is actually there. The stuff you can see—stars and gas—is made out of the same stuff as the sun; mostly hydrogen, some helium. The stuff you cannot see, called dark matter is...well, it is called dark matter. Nobody knows what it is.

About 80% of the matter in the universe is dark matter.[4] Describing a galaxy by saying it is made out of stars and gas isn't really accurate, in the same way that saying the sun is made out of helium isn't really accurate. Sure, there is some helium there, but most of the sun is not helium. Most of a galaxy is not stars and gas, it is dark matter.



Estimated distribution of dark matter and dark energy in the universe.

Image credit: NASA

I was feeling pretty pleased with myself now. This seemed like a mighty fine explanation. Then Mom reminded me I still hadn't answered the big question: If no one has ever seen this stuff why do grownups (with Ph.D.s no less) believe this stuff exists?

The short answer is that the dark matter that we cannot see pulls, through gravity, on the matter that we can see. We "observe" the dark matter indirectly through the influence it has on ordinary matter.

You experience this sort of indirect detection in everyday life. As an example, imagine you are hanging a heavy picture on a wall. You need to put the nail into one of the wooden studs that supports the wall because the studs are strong and can support a lot of weight. Unless you have transparent walls you can't see the studs, so what do you do? One way to find a stud is to use a small magnet, moving it along the surface of the wall. When you pass over a screw attaching the wall to the stud, the magnet tries to stick to the spot, pulling on your hand a bit. You cannot see the screw but you can detect it by the pull it exerts on the magnet.

Mom would have been happier, I think, if I stopped there. But once she got me started there was no stopping. How can you not get excited about mystery stuff that permeates the universe? To understand in detail the evidence for dark matter a little history is useful.

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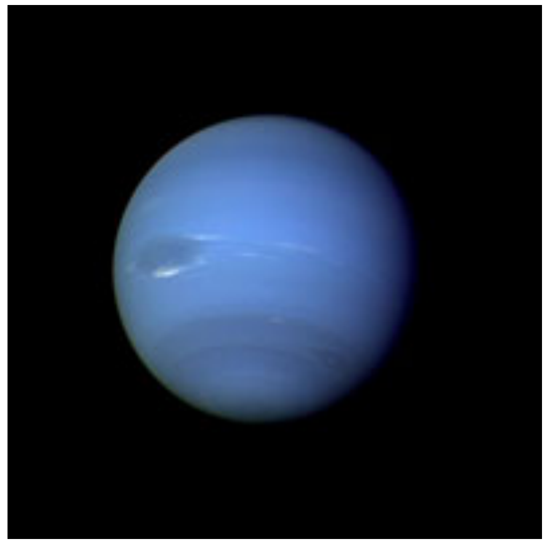
Mysterious motion of the planets

By the time the planet Uranus was discovered in 1781, Newton's laws of motion and of gravitation were about 100 years old. Astronomers immediately worked out what the orbit of Uranus should be given the six other planets known at the time: Mercury, Venus, Earth, Mars, Jupiter, and Saturn.

A funny things happened, though. Uranus didn't actually follow the orbit predicted by Newton's laws! Two solutions to the mystery were proposed. Either there must be another, as yet undiscovered planet, or Newton must be wrong. The first solution turned out to be correct. Astronomers used the observed motion of Uranus to work out where a new planet would have to be if Newton's laws were correct. Telescopes pointed at the predicted location discovered Neptune[5], and the mystery was solved.



The discovery of Neptune explained the mysterious motion of Uranus.

Image credit: NASA

This example illustrates that you can learn about something you can't see—Neptune in this case—from the motion of something you can see.

The planet Mercury also moved in a mysterious way[6]. Its orbit differed a tiny bit from the prediction made by Newton's laws, prompting a long search for the missing planet that must be causing the deviation. This mystery had a different resolution than the mystery of Uranus. Einstein demonstrated in 1915 that changing Newton's law of gravitation accounted for the mysterious motion of Mercury, and there was no missing planet.

This example illustrates that sometimes unusual motions indicate an incomplete understanding of the laws of nature.

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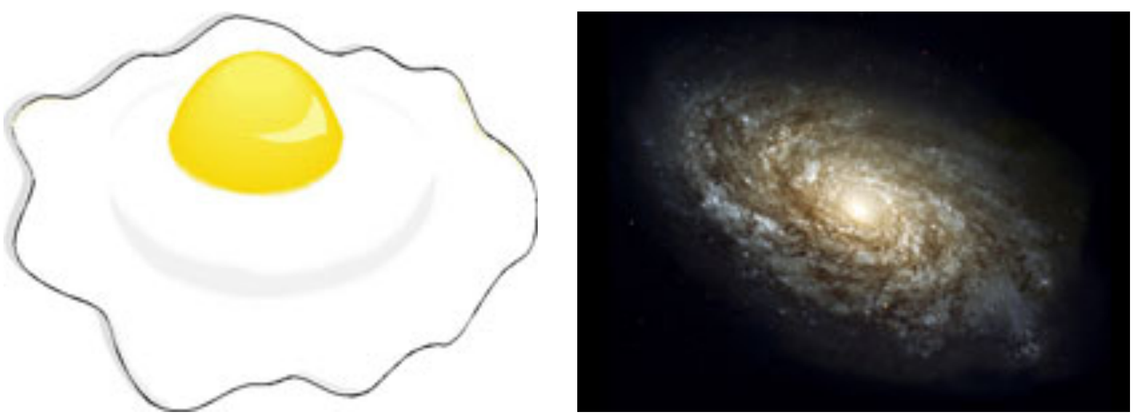
Mysterious motions of galaxies

A galaxy is a collection of billions of stars and clouds of gas. Spiral galaxies are flat, like a an egg fried sunny (no pun intended) side up. The central part of the galaxy, round like the yolk of an egg, is called the bulge. The outer parts of the galaxy, where the spiral arms are seen, is like the white of the egg, and is called the disc.

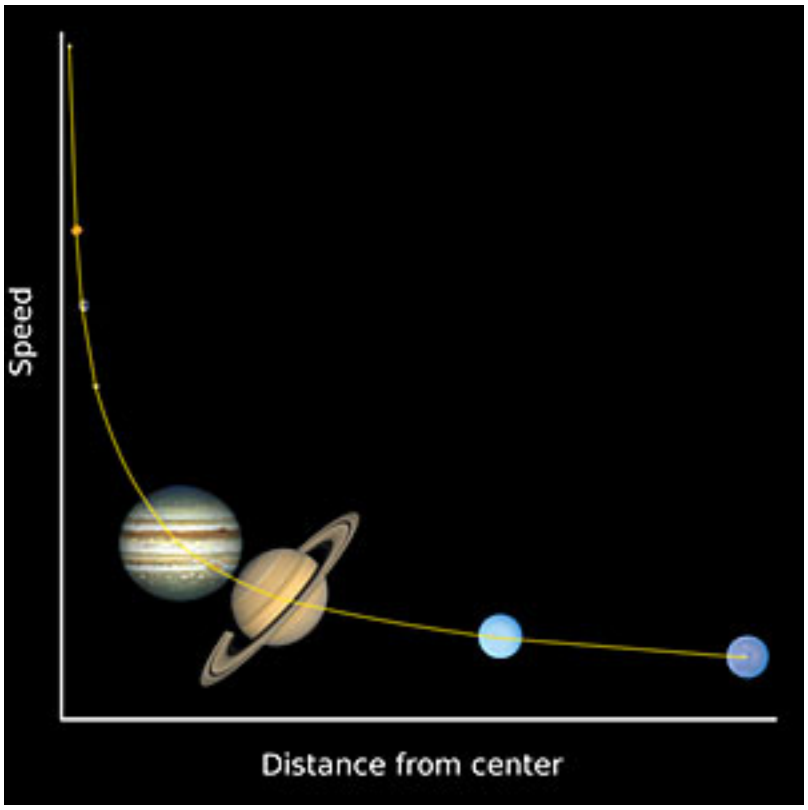


Spiral galaxies are shaped like sunny-side-up eggs – flat with a central bulge.

Image credit: Hubble Heritage Team (AURA/STScI/NASA)

The egg analogy is useful in another way. Much like most of the mass of an egg is in the yolk, most of the mass of the stars in a galaxy is concentrated in the bulge.

Unlike egg whites, stars in the disc move around the central bulge of a spiral galaxy in orbits shaped like the orbits of planets around our sun. Stars farther from the central bulge should move slower than stars closer to the center if the only matter in the galaxy is the stuff we can see. Planets in our solar system behave that way. Mercury, closest to the Sun, moves at a brisk 48 km/sec (107,000 mi/hr), while Neptune, the planet most distant from the Sun, moves at a relatively leisurely 5.4 km/sec (12,150 mi/hr).



The closer a planet is to the Sun, the faster it moves in its orbit. Stars should move similarly in galaxies, if the only matter in the galaxy is that which we can see.

Image credit: M. Craig

Now we get to the mystery. The actual motion of stars[7] in a galaxy is very different than this prediction. Stars farther from the center move faster than stars closer to the center!

What could the solution to this mystery[8] be? As with the mysterious motion of Uranus, there are two possibilities. Either there is matter we have not seen or Newton's law of gravitation is incorrect. The matter we haven't seen is called dark matter.

At first it seems easy to check which solution is correct. Just like the motion of Uranus indicated where to look for Neptune, the motion of stars in the disc indicate where to look for the dark matter. It should be spread throughout the entire galaxy, and in the outer regions over 90% of the galaxy should be dark matter.

You point the telescope to the right place, look, and you see....nothing, except the stars and gas you already knew were there. At this point you might suspect that this mysterious motion is like the motion of Mercury. Maybe there isn't any dark matter, but the laws of physics are incomplete.

Mom perked up a bit here and said, "I get it! You look for this stuff and you don't see it, so it isn't there, right?"

Fortunately the lighting was dim so she couldn't see me blush when I said "Well, actually it is there. It is just invisible."

After a long pause she asked "You mean invisible like the Invisible Man, you could see right through it?"

"Um, yeah, Mom. Like that".

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Invisible matter? Seriously?

The idea of invisible matter is not as crazy as it might seem. After all, light goes right through glass, so a flat piece of glass is "invisible" as far as light is concerned. I reminded Mom about the time I fell down after walking into a glass patio door, which made a couple useful points. Glass can be so invisible you don't even notice it, and a material like glass can be transparent to one thing, like light, and not to another, like budding physicists.

Dark matter is virtually transparent to everything. You could walk right through a patio door made out of dark matter and you wouldn't even feel it. If you can walk through dark matter, dark matter can pass right through you, and probably is right now. (Dark matter does not even stick to itself, so you could not really build a patio door out of it.)

Mom was back to looking skeptical. The only other good example of "invisible" matter I could come up with was neutrinos.

Fusion reactions in the core of the sun generate particles called neutrinos[9]. These neutrinos stream out of the sun and pass through the Earth 8 minutes later. Not only do they pass through people, they go right through the Earth. Even though about 1 trillion neutrinos pass through your body each second, only once in about 75 years will one of them interact with an atom in your body. Neutrinos are another example of "invisible" matter.

"Great, now you have an entire imaginary playgroup," Mom said. "First dark matter, now neutrinos, all invisible. Do you get paid for doing this stuff?"

Ouch. That hurt. Looking on the bright side, I saw an opportunity here and took it. Neutrinos, unlike dark matter, are observed in labs. Not many neutrinos interact even in a large detector, but the evidence that neutrinos exist is very concrete.

The history of neutrinos provides some hope that dark matter will eventually be detected in a lab. Wolfgang Pauli first guessed at the existence of neutrinos in 1930 based on energy that seemed to be missing in certain nuclear reactions. Neutrinos were not directly detected in a lab until 1956. Physics took twenty-five years from indirect evidence to direct evidence of the neutrino. Direct evidence of dark matter may take even longer to find, but several research groups[10] around the world look for it in a variety of different ways. For example, the Cryogenic Dark Matter Search II[11] looks for vibrations in a piece of silicon that might occur if dark matter went through the detector.

Detectors like this one, from the Cryogenic Dark Matter Search, are placed deep underground to try to detect dark matter.

Image credit: Cryogenic Dark Matter Search, University of California Berkeley

Mom, yawning now, accepted that neutrinos were real. She tried heading off for bed, but I insisted the rest of the evidence for dark matter was worth staying up for. She agreed, as long as the rest of the evidence took less than five minutes with no detours allowed.

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Other ways to "see" dark matter

Rotating spiral galaxies are not the only places dark matter makes its presence felt. Over the last two decades astronomers explored the question "If there really is dark matter, what are all the impacts it would have on the universe?" The circumstantial evidence accumulated clearly points to dark matter as the solution for the mysterious motion of galaxies.

The clearest example is gravitational lensing[12]. Think about the transparency of dark matter, and the analogy with the glass patio door again. Light passes through glass, but glass bends the path of the light through refraction. Dark matter lets light pass through; could it also bend the light as it passes? Yes.

The fix Einstein proposed for the law of gravity, the fix motivated by the mysterious motion of Mercury, also predicts that all mass should bend light. One of the early confirmations of Einstein's theory came during a total solar eclipse in 1919 in which the Sun bent the light of a star. Dark matter in a galaxy and, by extension, in a cluster of galaxies, should bend light passing through the galaxy or cluster. The curved arcs in the picture to the right are very distant galaxies whose image has been distorted by dark matter in a relatively nearby galaxy cluster. Dozens of examples like this demonstrate, completely independent of the motion of galaxies, that dark matter pervades space.

Here the "Gravitational Lens" of galaxy cluster Abell 1689 magnifies the light of distant galaxies. The gravity of the cluster's trillion stars -- plus dark matter -- acts as a 2-million-light-year-wide "lens" in space.

Image credit: NASA, N. Benitez (JHU), T. Broadhurst (Racah Institute of Physics/The Hebrew University), H. Ford (JHU), M. Clampin (STScI), G. Hartig (STScI), G. Illingworth (UCO/Lick Observatory), the ACS Science Team and ESA

With an eye on my watch, I just listed the rest of the evidence for dark matter[13]. The hope now was simply to overwhelm Mom with the sheer volume of evidence.

Dark matter affects the motion of the galaxies moving inside a cluster of galaxies, and the motion of the clusters relative to each other. On a larger scale, dark matter affects the overall curvature and expansion rate of the universe. Without dark matter there is no way to understand those motions.

Dark matter also provides the seeds for galaxy formation. Clumps of dark matter formed long before galaxies. Those clumps left an imprint on the cosmic microwave background[14] and provided the initial gravitational attraction to pull the raw material of a galaxy together.

Dark matter affected the universe from its earliest moments. The amount of dark matter directly influenced the amount of helium relative to hydrogen. The size of the universe at the time that dark matter began to dominate light as the main source of gravity left an imprint on the distribution of galaxies in the sky. This imprint provides another measurement of the amount of dark matter.

This combination of the many different types of evidence makes the case for dark matter compelling.

Hopefully, in the near future the evidence for dark matter will be direct. Mom and I would both be happier if the answer to the question "How do we know there is dark matter?" was simply "Because we can make it in a lab."

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About the Authors

Matt Craig is an associate professor of Physics and Astronomy at Minnesota State University Moorhead. He was director of the project Seeing is Believing, which included a small exhibit on dark matter (including an online game). According to his mother, he never actually walked into a patio door.

Components of Invisible Galaxies: Dark Matter & Galaxies, an interactive exhibit developed by the authors as part of Seeing is Believing.

Sara Schultz graduated from the University of South Carolina in December 2006 with her Master's degree in physics with a focus in astrophysics. She is currently volunteering on the planning board for the new Minnesota Planetarium and Space Discovery Center to be built in downtown Minneapolis, MN in 2009. As an undergraduate she worked on an informal public science education project to develop museum-like exhibits on current topics in physics, astronomy, and mathematics.

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Classroom Activity 1: Dark Matter Possibilities

Astronomers aren't yet sure what dark matter is, but they have some ideas. In this activity from NASA's Imagine the Universe[15], students research these possibilities using available resources. Students will organize their findings and present this information in a creative and engaging fashion.

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Classroom Activity 2: Dark Matter: Probing What You Can't See

Although astronomers cannot see dark matter, they can observe its effects. In this activity from NASA's Structure and Evolution of the Universe education forum[16], students in grades 9-12 will use several methods to determine what "hidden matter" lies between two paper plates. Through analogies associated with the cutting-edge research that is now going on with dark matter, they will uncover the "hidden matter" during this laboratory investigation.

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Resources

1. Introduction to Dark Matter
http://imagine.gsfc.nasa.gov/docs/science/know_l1/dark_matter.html

2. What is Dark Matter?
http://www.windows.ucar.edu/tour/link=/kids_space/dark_matter.html&edu=high

3. Ingredients of the Universe
http://cdms.berkeley.edu/Education/DMpages/essays/ingredients.shtml

4. What is the Universe Made Of?
http://map.gsfc.nasa.gov/m_uni/uni_101matter.html

5. The Discovery of Neptune
http://www1.jsc.nasa.gov/er/seh/neptune.html

6. Precession of the Perihelion of Mercury
http://physics.ucr.edu/~wudka/Physics7/Notes_www/node98.html

7. Orbital Mechanics of Galaxies
http://cosmology.berkeley.edu/Education/CosmologyEssays/Orbital_Mechanics.html

8. Dark Matter Mystery
http://chandra.harvard.edu/xray_astro/dark_matter.html

9. What's a Neutrino?
http://www.ps.uci.edu/~superk/neutrino.html

10. Dark Matter Experiments
http://cdms.physics.ucsb.edu/others/others.html

11. Explore the Science of Dark Matter (from the Cryogenic Dark Matter Search)
http://cdms.berkeley.edu/Education/DMpages/index.shtml

12. Gravitational Lensing
http://imagine.gsfc.nasa.gov/docs/features/news/grav_lens.html

13. Press release: NASA Finds Direct Proof of Dark Matter
http://chandra.harvard.edu/press/06_releases/press_082106.html

14. Cosmic Microwave Backgound Radiation
http://map.gsfc.nasa.gov/m_uni/uni_101bbtest3.html

15. Classroom Activity #1 – Dark Matter Possibilities

http://imagine.gsfc.nasa.gov/docs/teachers/galaxies/imagine/act_dark_matter.html

16. Classroom Activity # 2 – Dark Matter: Probing What You Can't See
http://universe.sonoma.edu/activities/dark_matter.html

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