ASTROEDU

Peer-reviewed Astronomy Education Activities

Dark matter & dark energy (Part 2) – Understanding the nature of dark matter and dark energy

What are dark matter and dark energy?

Tran Dong Thai Han, Leiden Observatory; Massimo Viola, Leiden Observatory; Henk Hoekstra, Leiden Observatory

AGE

12+

LEVEL

Middle School, Secondary, Informal

TIME

45min

GROUP

Group

SUPERVISED

Yes

COST PER STUDENT

Medium Cost

LOCATION

Small Indoor Setting (e.g. classroom)

CORE SKILLS

Developing and using models, Constructing explanations, Engaging in argument from evidence

TYPE(S) OF LEARNING ACTIVITY

Guided-discovery learning, Interactive Lecture, Problem-solving, Debate, Puzzle-based learning, Modelling, Fun activity

KEYWORDS

Dark matter, Dark energy, Invisible, Gravitational lensing, Gravity, Universe

SUMMARY

GOALS

- To realize the overwhelming evidence for dark matter and the ongoing search for defining dark matter and dark energy.
- To familiarize students with scientific thinking and working process.

LEARNING OBJECTIVES

- Students will use the concepts of gravity and orbiting speed of stars to reinforce the existence of dark matter in the Universe.
- Students will demonstrate how light is bent by gravity to explain the detection of dark matter with gravitational lensing.
- Students will construct arguments while discussing what dark matter is using what they already learn from the activity about properties of dark matter.
- Students will recognize the mysterious nature of dark matter and dark energy as they work like scientists, testing and eliminating different potential candidates.

EVALUATION

Listen to students arguments in the discussion on what dark matter is to see if student reasoning combines what they have learnt about dark matter.
At the end of the activity, ask students to explain how they know dark matter exists in the Universe. Students should:
- Mention the same orbiting speed of both the stars at the edge and the center of a galaxy.
- Describe gravitational lensing phenomenon.
- Mention that these are the result of the presence of dark matter creating gravity across the galaxy.

MATERIALS

- A PowerPoint presentation (in the attached material)
- A computer and projector for showing the presentation
- Large round washbowl (diameter minimum 30cm)
- Stretchy sheet (cut from stretchy fitted bed sheet)
- Elastic band (to fix the sheet on the wash bowl)
- Marbles (different sizes)
- Water
- Small beads
- Water color
- A wine glass
- A candle and candle holder (birthday cake type)
- A disposable cup
- A lighter
- Colored tape
- A saucer
- Magnet and a cardboard (a nail taped on the back)

BACKGROUND INFORMATION

Dark matter

Gravity allowed scientists to discover dark matter. In 1933, a Swiss astronomer, Fritz Zwicky tried to measure the total mass of a galaxy cluster by summing the mass of each individual visible galaxy in the cluster. He found out that their total mass was not enough to create the observed gravity that holds the galaxies together to form a cluster. With just the gravity created by all of their visible matter, the galaxies would not cluster easily, if at all. Thus, Zwicky concluded that there must be something invisible, inside and around the galaxies. This matter adds the extra mass to create that gravity, strong enough to form a galaxy cluster. Zwicky called this unseen mass, dark matter.

More evidence for dark matter has emerged over time. Photographs of galaxies showed that most of their light, i.e. most of their stars, were concentrated near the center of the galaxies. Therefore, most of the mass of a galaxy must be concentrated in its center, meaning that gravity is stronger at the center of a galaxy than in the outskirt. Because of this, it is expected that the stars near the center of the galaxy would move faster than those farther away. However, the measurements indicated that the orbital speed of stars was the same everywhere, regardless of their distance from the center. The conclusion is that there must be invisible matter that spreads throughout a galaxy, such that stars far away from the center will feel the gravitational pull of not only the central material, but all the other matter between them. The extra force of gravity from dark matter can cause them to speed up roughly to the same speed of the stars near the center.

The existence of Dark Matter is evident through an optical illusion, called gravitational lensing, seen as a result of light being bent by the gravity generated by dark matter. When viewing distant galaxies with telescopes, astronomers observed strange rings and arcs of light coming from a distant source, despite no observation of any mass. Light normally travels straight in space. The presence of mass creates gravity. Einstein discovered that gravity is the same as curvature of space, which causes light to travel along this curvature, instead of going in a straight line, i.e. light is bent. Therefore, the mass acts as a lens, called a gravitational lens, bending any light passing by. This indicates the presence of invisible mass that is creating the gravity and the phenomenon. Hence, dark matter can also be indirectly observed through gravitational lensing.

Although it's been discovered for some time, it's still unknown what dark matter really is. Scientists have proposed various ideas and designed experiments to test those ideas. However, the quest to define dark matter has, thus far,mainly been a process of elimination. Experiments have ruled out potential candidates, such as black holes, brown dwarfs, neutron stars, which are invisible or difficult to detect, but are not numerous enough to account for the additional mass in the Universe.

A current leading hypothesis is that dark matter is made of something different from the normal matter because it is invisible and does not interact with other normal matter that we are familiar with. Scientists think dark matter might be made of particles predicted by theory (exotic particles), however, they have been unable to find these particles yet. Scientists have also been trying to generate dark matter particles in large underground experiments where avoid contamination by other "normal" particles Can be avoided. In the absence of discovery of dark matter particles, some researchers suggest that the effects of dark matter could be explained by fundamentally modifying the theory of gravity. This idea proposes that at the scale of the Universe, gravity may act differently than on Earth, creating the effect that scientists interpret as dark matter.

Dark energy

Something even more mysterious, called dark energy, makes up 70% of the Universe, besides normal matter and dark matter. Normal and dark matter generate gravity which holds things together. Dark energy is completely opposite to gravity; it causes things to be pushed apart. To understand dark energy, think about what happens when you toss a ball up into the air. It goes up and gradually slows down due to the pull of gravity. Eventually, the ball stops in mid-air and falls back to the ground. Now imagine a ball, once tossed up, keeps flying up further and further, faster and faster, instead of being attracted back down to the ground. This event seems impossible to happen, but this is the property of dark energy.

In the 1990s, dark energy was discovered as astronomers observed such a peculiar effect in distant galaxies within the Universe. Scientists know that Universe has continually expanded, with galaxies moving away from each other, since its formation at the Big Bang. They also observed that the speed of expansion has increased, which is unexpected, because like the tossed ball, the expansion was expected to slow down as gravity pulled on all of the galaxies. Scientists had suspected that the Universe would stop expanding and finally collapse, if gravity won and halted the expansion. Scientists concluded that the accelerated expansion cannot be caused by dark matter and normal matter, which generate gravity for the Universe, but must be by some form of mysterious energy that acts as an force opposite to gravity. As it is invisible, they called it dark energy. Remember that the Universe has always been expanding; dark energy acts to accelerate this expansion. By measuring how fast the Universe is expanding over time, which is a combined effect of dark matter pulling galaxies together and dark energy pushing them apart, astronomers can determine the proportion between dark energy and dark matter.

Scientists have many theories, but no concrete answer yet, for the nature of dark energy. The different theories for dark energy differ in the way they predict the expansion of the Universe with time. Scientists are trying to take more accurate measurements of the acceleration of the Universe, to see which theory best explains dark energy and hope to understand what Dark Energy is. One other possibility suggested by some scientists is that maybe Einstein's theory of gravity is flawed and there is no dark energy after all. However, no one has been able to improve on Einstein's theory such that it can explain the effects of dark energy and also fit other phenomena of gravity. Dark energy remains one of the greatest mysteries of the Universe. If one day we understand dark energy, it will change what we already know and the way we think about the Universe.

FULL ACTIVITY DESCRIPTION

Introduction: (3 min)

1. To do this activity, the students need to have undertaken the first activity, part 1 (Discovering the main components of the Universe (Secondary school)). In part 1, they have played the role of scientists and found that

additional invisible mass exists in the Universe, besides the normal matter. They have also learnt about dark energy.

2. Ask students to explain their understanding about dark matter and dark energy from the previous activity. They should be able to explain that they are invisible and their nature is unknown. Dark matter creates gravity, while dark energy is the opposite to gravity.
3. Because of their mysterious nature, when saying something invisible and undetectable exists, there need to be solid proofs. In this activity, the students will need to find further evidence to support the claim that dark matter exists.

For each activity below, the class can be divided into small groups to do the activity. The teacher goes through the steps of the activity with students, giving instruction and explanation.

Part 1: More evidence for dark matter (15 min)

1. Cover a large round washing bowl with a stretchy sheet, the surface of the stretchy sheet is like a small portion of space in two dimensions.
2. Recap the concept that gravity is curvature of space. Place a heavy marble on the sheet and roll in a lighter marble. Students observe that the light one moves faster when it is near the heavy marble. Students then try to explain this observation. This is because the space closer to the mass is curved more, meaning the attraction by gravity is stronger.

3. Relate this observation with the solar system. The Sun is in the center of the system, it is the most massive and creates a strong gravity for other planets to orbit. Ask students what they expect for the speed of the innermost planets compared to the planets more at the edge in the Solar system. They should expect the planets closer to the Sun to orbit faster than those further.
4. Tell the students that the effect of gravity is seen as it causes objects to move and orbit. Recap from the previous session, they know dark matter is invisible mass. Ask the students to discuss and suggest how to prove dark matter existence, if the only observable effect is its gravity.
5. Help the students to get to the answer. By observing any irregular or unexpected orbit of stars in a galaxy, we can follow the trail of dark matter, left by its gravity. Scientists also often base their conclusions on what they can observe to deduce about what cannot be seen.
6. Tell the students that in a galaxy, most of the stars cluster near the center (use slideshow or printed image). Thus, most of the mass of the galaxy looks like it is concentrated at its center. The students would expect the stars near the center to orbit faster than those more at the edge.
7. Tell the students that in fact, unexpectedly all of the stars move at similar speed everywhere in the galaxy, similar to beads flowing in water.
8. Fill an empty washbowl with water. Just before throwing some beads into the water, paint some watercolor on the beads. Gently stir the water (avoid create a vortex) and throw in the beads. Observe the trails of color created by the beads.
9. Students compare flow speed of the beads at the edge and in the center of the bowl. The beads flow around in similar speed everywhere. Students then try to explain that because of the uniform distribution of water, the movement is the same everywhere in water.

10. Help the students to relate the two observations to prove the existence of dark matter. They should indicate that the unexpected uniform orbital speed of stars in galaxy reflects the acting of some invisible mass influencing gravity. Water in the activity acts like dark matter, invisible and evenly spreads across the galaxy. It causes uniform gravitational pull throughout a galaxy, causing what we observe with star orbital speed. This is a further evidence for the existence of dark matter in Universe.

Part 2: Gravitational lensing (10 min)

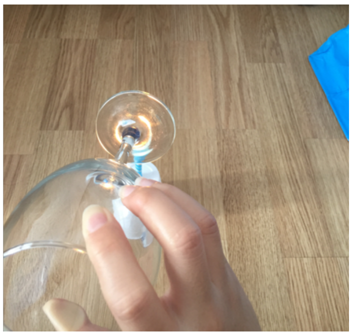
1. Explain to the students that scientists can indirectly observe dark matter as its gravity bends light. Use the background information to explain how light is bent by gravity.
2. Students then undertake this activity to understand how gravity bends light. Use some tape and create a straight line on a table surface. This represents light, which travels straight in space. Remind students about the stretchy sheet-wash bowl experiment. Something with mass will bend down the sheet i.e. creating gravity. Use a saucer to represent this curved space.

3. Partly remove and lift up one end of the tape that was pasted on the table, place the saucer (upside down) where the tape was before. Put down the tape and paste it again on the surface that is within its path (i.e. the saucer

and the table). The tape cannot be pasted smoothly in a straight line as before, but has to be bent; only then it can be pasted smoothly on the saucer surface and on the table surface.

4. Light being bent by gravity is a phenomenon called gravitational lensing. Show an image of gravitational lensing (using the accompaning slideshow or printed image). The presence of dark matter bends space, which can act like a lens, bending light from a distant source as it passes by.
5. Place a candle on a cup and use a wine glass to see the candle through the base of the glass. The candle is a distant light source. The base of wine glass acts as gravitational lens.

6. Help students to adjust the glass to see the candle light being distorted and forming a ring or arc of light. The distorted images mimic the gravitational lensing phenomenon observed by telescope. Emphasize that the glass base is not really creating gravity. It just represents the effect of something "invisible", like dark matter in front of the distant light source, distorting the path of the light before reaches us.



7. Tell the students that the presence of telescope images showing gravitational lensing, despite no observation of any object, indicates that there must be invisible mass creating the gravity. Hence, dark matter can be indirectly detected by the effect of gravitational lensing.

Part 3: What are dark matter and dark energy? (15 min)

1. It remains a mystery as to what dark matter really is, because it is invisible and does not interact with other normal matter that we know. Show some examples.
2. Turn off and on the light in the classroom allows visualization of objects and people. Dark matter does not interact with light to be seen.
3. Magnets allow detection of a hidden nail stuck on the back of a cardboard. Dark matter is not magnetic to be detected.
4. Use an X-ray image to show how X-ray, although invisible to naked eye, is absorbed in body and can be detected to create an image. Dark matter does not interact nor get absorbed. It cannot be detected at all.

5. Tell students that scientists have worked to eliminate many possible candidates of dark matter and they will play a small game to demonstrate. Print out each of the following notes in large fonts (so that the entire class can read). In each of these notes, some space objects are written as possible candidates for dark matter. There are descriptions and facts about each candidate.

   BLACK HOLES
   Result after large stars die (collapse).
   Have extreme gravity that captures anything that comes too close and prevents them from escaping.
   Even light is trapped inside black hole, that's why black holes are invisible.

   NEUTRON STARS
   Result after large stars die (collapse).
   Smallest and densest stars known to exist.
   A neutron star can be very small but has the mass of about twice the Sun.
   Rare.

   BROWN DWARFS
   Failed stars - lack enough mass needed to start burning.
   Emit no visible light.
   Rare.

   EXOTIC PARTICLES
   Exist in theories.
   Has mass.
   Interact very weakly with light and other normal matter.
   Invisible and undetectable.

6. A student blind-picks a note and paste it on the blackboard. As the class reads, they discuss and decide if that is the best candidate of dark matter and why. Then choose another note to discuss. They can change their decision about the previous candidate as they go through the notes.

   Note:

   If students need help, tell them that the hints are the bold-italic words. They can base on these words to form their explanations and arguments why this candidate should or should not be dark matter.

7. Once all the notes have been discussed and students have chosen their dark matter candidate, use background information to explain why black holes, neutron stars and brown dwarfs were eliminated, although they are invisible or difficult to detect. Because black holes and neutron stars are remnants of dead stars, so they are made of normal matter. Brown dwarfs are also made of normal matter as they are simply failed stars that cannot burn and shine. But dark matter does not react as normal matter. Moreover, these objects don't exist in enough quantity to account for the 25% mass of dark matter.
8. Use background information to explain about exotic particles and the ongoing research of dark matter. Also use background information to explain about the research trying to define dark energy. Then, emphasize to students the fluid nature of science work. It involves testing, finding evidence, eliminating alternative explanations to finally have an answer.

Importantly, keeping an open mind about changing one's own ideas is part of being a good scientist.

Part 4: Wrap up (5 min)

1. Conclude that it is still a mystery for what dark matter and dark energy really are. But there have been substantial proofs to support their existence.
2. Go through the entire activity with the students to point out how they have worked like a scientist. Working in the field of science means there will always be unexpected results, which must be carefully recorded as they may signal for something new to be discovered. To solve the mysteries, it requires observation, deduction, making hypothesis based on observation and available knowledge, and finding proof to support one's idea. Testing alternative theories to finally converge to one final, most plausible explanation is common practice in science.

CURRICULUM

ADDITIONAL INFORMATION

Before starting this activity, Part 1 - Discovering the main components of the Universe, is required to understand how scientists proved the existence of invisible dark matter and dark energy as the major components of the Universe.
The gravitational lensing activity is based on activities from Perimeter Institute for Theoretical Physics and from Inside Einstein's Universe Website.

CONCLUSION

In this activity, students play role of scientists to explore further proofs to support dark matter existence. They also learn about the ongoing research to define dark matter and dark energy to understand the nature of science work. This activity helps students develop scientific thinking and method of scientific investigation.

ATTACHMENTS

- Presentation
- Images for printing

ALL ATTACHMENTS

All attachments

CITATION

Han Tran; Massimo Viola; Henk Hoekstra , 2018, *Dark matter & dark energy (Part 2) – Understanding the nature of dark matter and dark energy* , astroEDU,

ACKNOWLEDGEMENT

Pedro Russo, Cristina Nicolaita