Cosmic Explosions

Applying Newton's Laws on a Massive Scale

Purpose

In this lesson, students learn about current research into the forces acting on galaxies in our universe, including gravitational forces that attract galaxies to each other and a mysterious force that is pulling galaxies away from each other. Applying Newton's Laws, students describe the motion of galaxies and the forces between galaxies that govern those motions.

Audience

This lesson was designed for use in an introductory high school physics course.

Lesson Objectives

Upon completion of this lesson, students will be able to:

- describe forces acting on galaxies.
- compare the magnitudes of gravitational forces between different celestial bodies using Newton's Law of Universal Gravitation.
- discuss action-reaction force pairs in the context of force between galaxies.
- describe hypotheses related to dark energy and the formation of galaxies.

Key Words

cosmology, gamma ray bursts

Big Question

This lesson addresses the Big Question "*Where do we come from?*"

Standard Alignments

- **Science and Engineering Practices**
    - **SP 5.** Using mathematics and computational reasoning
    - **SP 7.** Engaging in argument from evidence

- MA **Science and Technology/Engineering Standards (2016)**
  - **HS-PS2-4.** Use mathematical representations of Newton's Law of Gravitation and Coulomb's Law to describe and predict the gravitational and electrostatic forces between objects.
  - **HS-PS2-10(MA).** Use free-body force diagrams, algebraic expressions, and Newton's laws of motion to predict changes to velocity and acceleration for an object moving in one dimension in various situations.
- **NGSS Standards (2013)**

  HS-PS2-4. Use mathematical representations of Newton's Law of Gravitation and Coulomb's Law to describe and predict the gravitational and electrostatic forces between objects.
- **Common Core Math/Language Arts Standards**

  CCSS.ELA-LITERACY.RST.9–10.1. Cite specific textual evidence to support analysis of science and technical texts, attending to the precise details of explanations or descriptions.

Misconception Addressed

- This lesson addresses a common misconception about forces, that in an action-reaction pair the object with greater mass exerts greater force. (Question 6)
- Further information about student misconceptions on this topic can be found here.

Primary Sources

- **Bite** "Galactic Forces in Action" *based on*:

  Piran, Tsvi, Raul Jimenez, Antonio J. Cuesta, Fergus Simpson, and Licia Verde. "Cosmic Explosions, Life in the Universe, and the Cosmological Constant." *Physical Review Letters* 116, no. 8 (2016). doi:10.1103/physrevlett.116.081301.
- **Misconceptions**

  Hestenes, David, Malcolm Wells, and Gregg Swackhamer. 1992. "Force Concept Inventory." *The Physics Teacher* 30 (3): 141–58. doi:10.1119/1.2343497.

Materials

- Metric ruler, one per student
- Copies of Student Handout and Science Bite for each student

Time

This lesson should take approximately one 50-minute class period.

Student Prior Knowledge

This lesson requires prior knowledge of Newton's Law of Universal Gravitation as well as Newton's second and third laws of motion. No familiarity with dark energy is expected.

Instructions and Teacher Tips

- **General Procedure**
  - Lead an opening discussion, see "Big Question Discussion" below.
  - Distribute copies of the Bite and the Student Handout.
  - Have students read the Bite and annotate as they read. One idea for annotation would be to have students circle words or phrases they find interesting, underline words or phrases they don't understand, put an "!" next to anything they find surprising, and write a "?" next to anything they have a question about.
  - Have students answer the text-dependent questions (Questions 1–5) and the analysis questions (Questions 6–9)
  - Review answers to questions if desired.
  - Lead a wrap-up discussion, see "Big Question Discussion" below.
- **Tips, Extensions, and Variations**
  - It is important for students to precisely measure arrow lengths throughout. Please check that figures printed at an appropriate size. You may want to prompt them to measure from the center of mass to the tip of each arrow.
  - This lesson is well-suited to reading out loud in pairs or small groups.
  - Consider having students work in small groups to answer the questions.

Background Information and Research Details

- For nearly a century, scientists have recognized that our universe is expanding. American Astronomer Edwin Hubble is widely recognized for discovering this fact in 1929 based on observations of the velocity and distance of galaxies around the Milky Way. (Hubble had to first demonstrate that these distant collections of stars are in fact other galaxies; a highly controversial claim at the time!) He showed that all distant galaxies are moving away from the Milky Way, and that more distant galaxies are moving away even faster. The best cosmological model to explain these observations is an expanding universe, where all galaxies are simultaneously moving away from each other. For more information about Hubble's discovery, see this site from the Sloan Digital Sky Survey.
- How do we know that dark energy exists? While several lines of evidence convincingly point to the existence of dark energy, perhaps the most influential has been observations of distant exploding stars called supernovae. Because the brightness of a supernova can be estimated precisely, it can be used as a "standard candle" to derive the distance to the

galaxy the star exploded. Astronomers in the 1990s used supernovae to map out the direction and speed of many different galaxies relative to the Milky Way. They shocked the scientific community by demonstrating that the galaxies furthest from us are moving away much faster than Hubble would have expected, suggesting a positive acceleration to the expansion of the universe. The Nobel Prize in Physics in 2011 recognized teams of astronomers that contributed to these observations. For more information about this Nobel Prize, see this site from the Nobel Foundation.

- This lesson discusses dark energy, but many students may also have heard of dark matter. These are two distinct concepts resulting from two different physical phenomena. Dark matter is a substance that has mass and generates gravitational force, just like normal ("baryonic") matter, but does not interact with light in the way normal matter does. Massive clumps of regular matter tend to generate very bright sources of light, like stars and galaxies, but massive clumps of dark matter seem to generate no light of any kind. Astronomers have precisely measured the mass of dark matter in the universe and found that the total mass of dark matter in the universe is more than five times the total mass of regular matter.
- But dark matter and dark energy are connected in that they contribute to the pulling forces that govern how our universe formed and is evolving. They are both relatively recent (twentieth century) discoveries that we still have much yet to learn about.
- What is, or what causes, dark matter and dark energy? The short answer is that we really don't know yet. While we can measure the effects of dark matter and observe indirectly that it exists, dark matter is not a substance that we've been able to isolate and hold in our hands or study under a microscope. There are, however, many very plausible and exciting theories that provide potential answers to these questions. Many physicists and astronomers today are working to devise new tests to help us prove or disprove these various ideas.
- Do dark matter and dark energy really exist? The vast majority of physicists and astronomers agree that yes, it does. There are now several very strong lines of evidence each with many independent observations that point convincingly to their existence: not just the velocity of distant galaxies and exploding stars, but also sensitive measurements of the cosmic microwave background radiation, the velocity curves of stellar rotation in galaxies, and more.
- For more information about dark matter and dark energy see sites from Quantum Diaries, Scientific American and Phys.org, and NASA.

Big Question Discussion

This lesson should get students thinking about the Big Question "*Where do we come from?*" In particular, "*What makes life possible?*" If you choose to delve into the Big Question, consider the following ideas:

- To open a discussion, ask students what they know about the origin of the universe. Have they heard of the Big Bang? Do they think it is worthwhile to try to understand how the universe is evolving now and how it will change in the future? Are these types of questions about simple curiosity or might it have some other purpose?

- To wrap-up the lesson, have students share their answers to Question 12 (Why do you think this research matters?) in pairs or small groups. Then discuss it as a whole class. You may want to frame the search for knowledge and understanding as a fundamental part of human history in order to help students develop an appreciation for the value of this work.

Answers

1. Explain what causes clusters of galaxies to form.

Forces that push galaxies together, namely gravity, cause clusters of galaxies to form.

2. What law explains the attractive forces between galaxies? How is this law relevant to everyday life on Earth?

Newton's Law of Universal Gravitation, it is the gravitational attraction between masses that keeps objects and living things on Earth. It is also this attraction that keeps the Moon in orbit around the Earth and the Earth in orbit around the sun. This Law explains why objects fall toward Earth when dropped and why they remain on Earth's surface.

3. How do scientists know that the forces pushing galaxies together are smaller than the forces pulling galaxies apart? Explain in terms of galactic motion.

There is a net acceleration of galaxies moving apart.

4. Scientists have proposed that too much dark energy would have prevented the existence of life in the universe. What do they base that claim on?

Too much pulling force (dark energy) would have prevented the formation of dense galaxies.

5. Describe a gamma ray burst and explain whether they are life-promoting or life-inhibiting. Include a quote from the Bite to support your answer.

A gamma ray burst is a high-energy destructive explosion Gamma ray bursts are life-inhibiting. According to the text, gamma ray bursts occur in the Magellanic Clouds. The text goes on to say "If the gravitational force dominates and pushes all galaxies close together, the authors suggest, then even stars in big galaxies, like our Sun, will form in close proximity to many small satellite galaxies, like a myriad of Magellanic Clouds, that will overwhelm life with dangerous numbers of these destructive explosions [gamma ray bursts]". This sentence clearly implies that gamma ray bursts are destructive and counter to life formation.

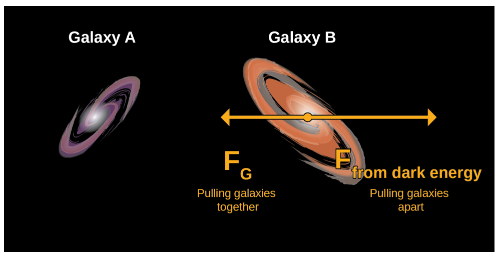

Figure 1 from the Bite is shown below, with the addition of the letters A and B to distinguish between the two galaxies.

6. Use **Figure 1** to answer the following questions.

NOTE! Figures 1–3 have been reduced in this Educator Document to save space. Do not use them for measurements.

a. Using a metric ruler, measure the length of the gravitational force (F_G) force arrow to the nearest 0.1 cm.

2.4–2.6 cm

b. Using a metric ruler, measure the length of the force from dark energy ($F_{\text{from dark energy}}$) force arrow to the nearest 0.1 cm.

3.4–2.6 cm

c. Given that the arrow length is proportional to the magnitude of the forces, which force is stronger, F_G or $F_{\text{from dark energy}}$?

$F_{\text{from dark energy}}$

d. What direction is the net force acting on Galaxy B? Justify your answer using evidence from the diagram.

The net force is to the right (same direction as $F_{\text{from dark energy}}$). The vector sum is to the right.

e. What direction is Galaxy B accelerating? How do you know?

Galaxy A is accelerating to the right as that is the direction of the net force.

f. Suppose Galaxy B has a mass that is 3 times smaller than Galaxy A. How does the force Galaxy B exerts on Galaxy A compare to the force Galaxy A exerts on Galaxy B in terms of both magnitude and direction? Support your answer by referring to one of Newton's Laws of Motion.

The force exerted by Galaxy B on Galaxy A is equal in magnitude and opposite in direction to the force exerted by Galaxy A on Galaxy B. The two galaxies are an action-reaction force pair and according to Newton's third law they exert equal and opposite forces on each other.

g. Measure the distance between the center of Galaxy A and the center of Galaxy B in the Figure 1 diagram above to the nearest 0.1 cm.

6.0–6.2 cm

Figure 2 below shows the positions of Galaxies A and B at a later time than in **Figure 1.**

7. Use **Figure 2** to answer the following questions.

a. Measure the distance between the centers of Galaxies A and B in Figure 2 above to the nearest 0.1cm.

12.2–12.4 cm

b. How does the distance in **Figure 2** compare to the distance in **Figure 1**?

The distance in Figure 2 is twice as great as that in Figure 1.

c. How does the gravitational force of attraction F_G between the two galaxies in **Figure 1** compare to that in **Figure 2**? (Choose the best answer below, then justify your choice).

i. F_G in Figure 1 is twice as great as in Figure 2

ii. F_G in Figure 1 is four times as great as in Figure 2

iii. F_G in Figure 1 is equal to that in Figure 2

iv. More information about the masses of the galaxies is needed.

Explain your answer choice.

The gravitational force between two objects is proportional to the inverse square of the distance between the two objects according to Newton's Law of Universal Gravitation. As the distance between the galaxies in Figure 1 is half the distance as the distance between the two galaxies in Figure 2, and the inverse square of one-half is four (mathematically $0.5^{-2} = 4$), the gravitational force is four times greater in Figure 1 than in Figure 2.

Figure 3 below shows Galaxy A and another of its neighboring galaxies, Galaxy C.

8. Use **Figure 3** to answer the following questions.

a. Measure the distance between the center of Galaxy A and the center of Galaxy C in the **Figure 3** diagram above to the nearest 0.1 cm. How does this compare to the distance between Galaxy A and B in **Figure 2**?

12.2 -- 12.4 cm, the distance is about the same.

b. Galaxy C has a mass three times that of Galaxy B. How does the gravitational force of attraction F_G between Galaxies A and C compare to that between Galaxies A and B in Figure 2?

i. F_G between A and C is three times as great as that between A and B

ii. F_G between A and C is nine times as great as that between A and B

iii. F_G between A and C is the same as that between A and B

iv. More information about the masses of the galaxies is needed to make a comparison.

Explain your answer choice.

The mass of Galaxy C is three times the mass of Galaxy B and each is the same distance from Galaxy A. According to Newton's Law of Universal Gravitation the gravitational force between two objects is directly proportional to each mass. Thus the gravitational force between A and C is three times greater than the gravitational force between A and B.

9. **Connect to the Big Question**. Astronomers engaged in research about dark energy and the origin of the universe are trying to learn more about where we come from and the conditions that led to human life on Earth. Why do you think this research matters?

Student answers may vary. *Sample responses:*

- it may help us to identify other places in the universe where life can exist.
- It may help us to understand other phenomena related to life on Earth, like how dark energy affects us.
- It could help us predict if there are going to be cosmological events that affect Earth in the future.
- Space is just fascinating, and people want to understand it just to know.