Understanding Runaway Stars Using Newton's Laws

Purpose

The purpose of this lesson is to apply Newton's first and third laws of motion and the Law of Universal Gravitation to understanding the phenomenon of runaway stars observed by astronomers.

Audience

This lesson was designed to be used in an introductory high school physics or astronomy elective course.

Lesson Objectives

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

- apply Newton's Universal Law of Gravitation to explain the effect of the force between two objects on each object's motion.
- explain the runaway stars phenomenon using Newton's first law and Newton's third law.

Key Words

binary stars, Newton's first law of motion, Newton's third law of motion, runaway stars, star clusters, universal gravitation

Big Question

This lesson addresses the Big Question "*What does it mean to observe?*"

Standard Alignments

- **Science and Engineering Practices**

  SP 2. Developing and using models

- **MA Science and Technology/Engineering Standards (2016)**

  - **HS-PS2-4**. Use mathematical representations of Newton's law of gravitation and Coulomb's law to both qualitatively and quantitatively describe and predict the effects of 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: One force in an action-reaction pair can be larger than the other. (Question 1b)
- Further information about student misconceptions on this topic can be found here.

Primary Sources

- **Bite** "Where Do Runaway Stars Come From?" based on:
  - McEvoy Catherine M., Philip L. Dufton, Jonathan V. Smoker, David L. Lambert, Francis P. Keenan, Fabian R. N. Schneider, and Willem-Jan de Wit. 2017. "The Origin of B-Type Runaway Stars: Non-LTE Abundances as a Diagnostic." *The Astrophysical Journal* 842(1): 32. doi:10.3847/1538-4357/aa745a.
  - Winkler, P. Frank, Gaurav Gupta, and Knox Long. 2002. "The SN 1006 Remnant: Optical Proper Motions, Deep Imaging, Distance, and Brightness at Maximum." *The Astrophysical Journal* 585: 324–335. doi:10.1086/345985
- **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

- Copies of the Student Handout and Science Bite for each student
- About two meters of rope or string

Time

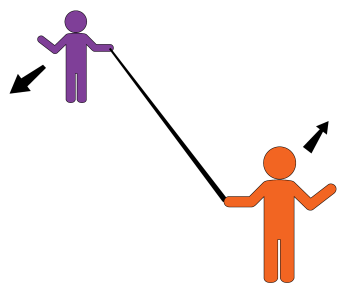
This lesson should take approximately one 50-minute class period.

Student Prior Knowledge

Students should be familiar with forces, especially gravitational force. Students should also be familiar with Newton's laws and circular motion.

Instructions and Teacher Tips

- **General Procedure**
  - Have students read through the introduction in the student document.
  - Review the key points of the introduction with the class.
  - Circular Motion Demo (see diagram below)
    - Have two students hold a rope, one on each end.
    - Have the two students gently pull on the rope.
    - Each student should attempt to walk at a 90 degree angle to the rope in opposite directions from each other (see diagram below).



    - This will result in students orbiting around each other.
    - Have one student let go of the rope suddenly (but gently) and have the class observe what happens to the other student. The other student should continue walking in a straight line.
  - Hand students the Bite and the student handout. They will read the article and answer the questions.
- **Tips, Extensions, and Variations**
  - The handout includes a flowchart about Newton's laws as well as the universal gravitation equation for students' reference. If students have just studied this material, the introduction may not be necessary.
  - If you use the Bite as it is formatted on the BiteScis website, you can tell students to read the front page, answer Question 2, then read the back page and answer the rest of the questions.
  - For older or more advanced students you may choose to have them just read the entire Bite and answer all of the questions.
  - A common misconception that may have is that if one student pulls harder on the rope during the demonstration that the other student will experience a greater force. Newton's

third law of motion refutes this claim—no matter how hard one student pulls, each student will experience the same amount of force. You may wish to discuss Question 1 part b with the class before having all students move on to make sure students understand this point. You can also demonstrate this by having students tie spring scales to each end of the rope and measuring the forces.

- The Bite does not provide a conclusive answer to the causes of runaway stars. This is a great opportunity to discuss with students how there are many phenomena that scientists are still trying to explain. Often when searching for the answer to one question, scientists develop many more questions.
- You may wish to discuss Question 1 part c in more depth if you have already covered circular motion and tangential velocity.
- Question 2b may be omitted if there is not a focus on circular motion.
- There is a PHeT simulation related to planets orbiting around each other that can be helpful for further discussions about gravitational force and orbit.
  - You can show the force and velocity vectors to have a conversation about what keeps one object orbiting the other.
  - There is also an option to turn off gravity and observe what happens to the motion of the orbiting object.

Big Question Discussion

This lesson should get students thinking about the big question "*What does it mean to observe?*" In particular, how do scientists make and explain observations about the universe? If you choose to delve into the Big Question, consider the following suggestions:

- Consider a class discussion about how it is impossible to observe the universe in real-time. The last question in the lesson asks students to think about how astronomers use light that is billions of years old to study the universe. This allows them to create a timeline of the universe by studying objects that are close to Earth ("younger" light) and objects that are further from Earth ("older" light). This is a new concept to many students and can lead them to have many sub-questions about what it means to observe and how scientists can use observations in novel ways.
- Another possible wrap-up discussion could involve a brainstorming session in which students brainstorm and think about other scientific concepts they might use to explain the phenomenon of runaway stars. The Bite is based on a paper that proposes one possible way in which the observations of runaway stars can be explained, can your students come up with others?

Background Information and Research Details

- This lesson shows how scientists are grappling with a phenomenon using simple concepts that students are learning in conceptual physics while also addressing a topic that students are naturally curious about, the universe.

- The universal gravitation equation often seems daunting to students. This lesson provides an opportunity for them to engage with that equation on a conceptual level with real life scientific mysteries about the universe.
- Supernova explosions are thermonuclear in nature, and propel the material from the star away at speeds up to 10% of the speed of light! These explosions can produce heavy elements, like gold and uranium. It is thought that all the elements on earth heavier than iron originally came from supernovae.
- Some theories of the ways in which stars are born require almost all stars to be born in a binary system. Because of this, some astronomers are searching for a star that could have been the sun's "birth twin."

Answers

1. Watch the demo of two students rotating around each other.

a. What keeps the two students orbiting around each other?

Both students exert a force on the rope that is connecting them. This force is what keeps them orbiting around each other.

b. According to Newton's third Law, what can you say about the magnitudes of the forces that each of the two students experiences? Are they equal or not? Explain.

Newton's third law says that for every action there is an equal and opposite reaction. Therefore, the forces that both students experience from pulling the rope is equal in magnitude.

c. What happens to the second student when one of the students lets go of the rope all of a sudden?

When one student lets go of the rope, the other student goes "flying off" in the direction their velocity vector was pointed.

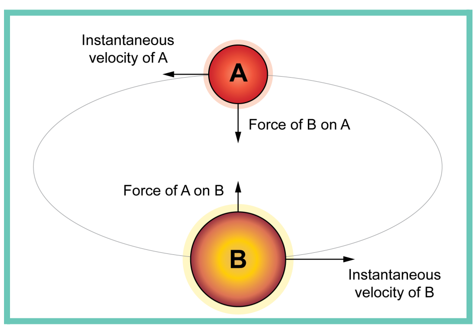
2. Read the first two paragraphs of your Science Bite article.

a. What is a binary star system?

A binary star system is composed of two stars that form in close proximity to each other and exert a large amount of gravitational force on each other. These two stars orbit around each other at a high velocity.

b. Thinking about the student model and what you read about binary stars, draw a model of what a binary star system might look like. In your model include labeled arrows that represent the force on each star from the other star and the instantaneous velocity vectors of each star.

Sample model:



The two stars may be different sizes (many binary systems have stars with different masses), but no matter the relative size of the two stars, the two force vectors must be the same size in order to obey Newton's third law. The direction of the binary star system's rotation depends on the viewing angle, so students could correctly reverse the direction of the velocity vectors. The viewing angle shown here is almost perpendicular to the plane of the orbits.

c. Use the orbiting student demo as an analogy of binary stars. What does the rope represent for binary star systems?

The rope represents the gravitational pull between the two stars that keeps them orbiting around each other.

d. What do you think might happen if one of these massive, fast moving stars in a binary system were to suddenly disappear? Explain using the Law of Universal Gravitation.

The other star would go "flying off" at a high velocity just like the second student in the rope demonstration. This is because if one of the masses disappeared, then m1 would be zero, and according to the equation for the Law of Universal Gravitation, the gravitational force between the stars would also equal zero.

3. Answer the following questions about supernovae in binary star systems.

a. What happens to the mass of a star during a supernova explosion?

It disintegrates into space and only a tiny dense core is left behind where the star used to be.

b. Look at the Law of Universal Gravitation in the Introduction section above. What is the relationship between the gravitational force between two objects and the masses of those objects?

The bigger the mass of one or both objects, the bigger the gravitational pull between them.

c. What would happen to the amount of gravitational force between the two stars in a binary system after a supernova explosion of one of them? Use the Law of Universal Gravitation to explain your answer.

Newton's Law of Universal Gravitation says that the magnitude of the force between two objects is directly related to the masses of the objects. Therefore, the gravitational force would decrease drastically because the mass of one of the stars decreases enormously.

d. Multiple Choice: Because the two stars in the binary system were so close in proximity, they were orbiting each other at a very high speed. What do you expect would happen to the motion of the second star after one of the stars explodes? Choose one of the options below and explain your answer.

i. It would keep moving around in its orbit at the same speed as before

ii. It would keep moving around in its orbit at a slower speed than before

iii. It would come to a crashing halt

iv. It would be propelled out of its orbit at a very high velocity

Explain your choice.

The star had a force on it before which kept it in orbit. Once the force is gone, the star would move away from the orbit in the direction of its tangential velocity.

4. Once the runaway star makes it out into empty space, it will continue in a straight line indefinitely, since there are no other external forces to change its velocity. Explain why this is using Newton's first law of motion.

Newton's first law is about inertia. It says that an object in motion will stay in motion unless acted upon by an outside force. Since the star is outside of the gravitational force field of the other stars in the clusters, this means that there are no outside forces acting on it. Therefore, the runaway star would stay in motion at a constant speed and in the same direction forever.

5. **Connect to the Big Question**. Making observations in astronomy has many unique challenges and interesting opportunities.

a. In the Science Bite you read, the researcher, Dr. Catherine McEvoy, wasn't able to come to a specific conclusion about what causes runaway stars. What information would help scientists better understand the causes of runaway stars? Do you think we will ever be able to obtain that information? What does that say about the limits of our observations?

Student answers may vary. *Sample response:* Scientists are limited by the equipment available to them (there are a limited number of telescopes and what those telescopes can observe is limited). They are also limited in the time that they can observe (you can only use some telescopes at night and often telescope time is very expensive). If we were able to collect more information about the chemical composition of stars, we would be better able to understand the causes of runaway stars. We may never be able to get that information depending on the technology we are able to develop. We are limited in our observations by the tools that we have and the ways in which we are able to analyze that data.

b. In astronomy, researchers are often looking at light that is billions of years old. What unique advantages does that give researchers when they are trying to use observations to develop an understanding of the universe? What limitations does that create?

Student answers may vary. *Sample response:* Scientists are also only able to study the light that reaches the Earth. As light from distant stars can take billions of years to reach us, we are often looking at a much different universe than the one we exist in now. This limits what we can understand about our universe as it exists now. The advantage is that we can create a history of the universe by looking at light that reaches us from further away (representing older events) and comparing to light that reaches us from close be (representing more recent events).