Molecular Energy and Earth's Atmosphere

What Happens When a Planet Forms Near a Black Hole?

Purpose

This lesson has students apply their understanding of energy conversions and molecular energy to describe how the atmospheres of rocky planets might form.

Audience

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

Lesson Objectives

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

- explain energy conversions that occur in Earth's atmosphere.
- calculate the kinetic energy of molecules in the atmosphere.
- describe current research related to what can create thin atmospheres on rocky planets.

Key Words

escape velocity, photoevaporation

Big Question

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

Standard Alignments

- **Science and Engineering Practices**
  - **SP 2.** Developing and using models
  - **SP 5**. Using mathematics and computational thinking
- **MA Science and Technology/Engineering Standards (2016)**
  - **HS-PS3-1**. Use algebraic expressions and the principle of energy conservation to calculate the change in energy of one component of a system when the change in energy of the other component(s) of the system, as well as the total energy of the system including any energy entering or leaving the system, is known. Identify any transformations from one form of energy to another, including thermal, kinetic, gravitational, magnetic, or electrical energy, in the system.
  - **HS-PS3-2**. Develop and use a model to illustrate that energy at the macroscopic scale can be accounted for as either motions of particles and objects or energy stored in fields.

- **NGSS Standards (2013)**
  - **HS-PS3-1**. Use algebraic expressions and the principle of energy conservation to calculate the change in energy of one component of a system when the change in energy of the other component(s) of the system, as well as the total energy of the system including any energy entering or leaving the system, is known. Identify any transformations from one form of energy to another, including thermal, kinetic, gravitational, magnetic, or electrical energy, in the system.
  - **HS-PS3-2**. Develop and use a model to illustrate that energy at the macroscopic scale can be accounted for as either motions of particles and objects or energy stored in fields.
- **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.

Misconceptions Addressed

- This lesson addresses two common misconceptions about heat transfer and energy. Including:
  - Heat is transferred from the sun to Earth. (Question 8)
  - Collisions of molecules produce heat or energy. (Question 5)
- Further information about student misconceptions on this topic can be found here.

Primary Sources

- **Bite** "The Mystery of the Missing Atmosphere" *based on*:

  Chen, Howard, John C. Forbes, and Abraham Loeb. 2018. "Habitable Evaporated Cores and the Occurrence of Panspermia Near the Galactic Center." *The Astrophysical Journal* 855(1). doi:10.3847/2041-8213/aaab46.
- **Misconceptions**

  Erceg, Nataša, Ivica Aviani, Vanes Mešić, Matko Glunčić, and Gordana Žauhar. 2016. "Development of the Kinetic Molecular Theory of Gases Concept Inventory: Preliminary Results on University Students' Misconceptions." *Physical Review Physics Education Research* 12(2).

  Pathare, S R, and H C Pradhan. 2010. "Students' Misconceptions about Heat Transfer Mechanisms and Elementary Kinetic Theory." *Physics Education* 45(6): 629–34.

Materials

- Copies of the Student Handout and Science Bite for each student
- Scientific calculator for each student

Time

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

Student Prior Knowledge

Students should be familiar with the principle of conservation of energy, gravitational potential energy and kinetic energy and how they are quantified, basic algebraic operations, and scientific notation. Additionally, they should understand that energy is converted from one form (e.g., gravitational potential, kinetic, thermal) to another in many processes

Instructions and Teacher Tips

- **General Procedure**
  - Instruct students to read the Introduction on the Student handout and answer the first two analysis questions.
  - Distribute the Science Bite and tell students to read and annotate it. One option for annotating is to have students star main ideas, underline new vocabulary, and put a question mark next to phrases they find confusing. This will help students remember key information and ask questions.
  - Have students answer the remaining analysis questions.
  - Discuss the answers to the questions and the research discussed in the Bite as a class.
- **Tips, Extensions, and Variations**
  - To support student success on Question 11, it might be helpful to review how to use numbers in scientific notation with their scientific calculators if that is not a task students regularly perform.
  - If you have struggling readers or English language learners, consider having students read the Introduction and/or Bite aloud in small groups. Or read it aloud to them yourself.
  - Consider having students work in pairs or groups of 3–4 to complete the questions.

Background Information and Research Details

- Several interacting processes contribute to a planet's ability to retain an atmosphere. In addition to photoevaporation, forcing pressure from a star's stellar winds (which can be mitigated by the presence of a strong planetary magnetic field or "magnetosphere"), kinetic energy from volcanism or other heating sources that speeds up gas molecules beyond the escape velocity ("thermal escape"), and catastrophic collisions can all serve as sinks that eject gases from a planetary atmosphere. Processes like delivery of ices and volatile materials from impacting objects (e.g., small asteroids and other stellar system debris), outgassing through volcanic activity, and weather processes between the planet's crust and atmosphere like the Earth's water cycle serve as sources which contribute to gasses in planetary atmospheres. See this paper by Helmut Lammer for more information.

- A striking contrast of the balance of these source and sink processes in our own solar system are Venus and Mercury. Mercury, extremely close to the sun and with a very small mass, has lost almost all of its atmosphere due to solar wind forcing, thermal escape, and other sink processes. Venus has retained a very dense atmosphere. It's being more massive and a little farther away from the sun than Mercury certainly helps limit photoevaporation and other escape processes, but does not explain why Earth and Mars (which are further from the sun than Venus) have much less dense atmospheres. The answer to why Venus' atmosphere is so dense seems likely to be a combination of orbital, chemical, and magnetic factors. See this paper in Space Science Reviews for more information.
- How long does the photoevaporation process take? It depends on the intensity of the radiation the planet is receiving, its mass, atmospheric characteristics, etc. But generally it will take tens to hundreds of millions of years to substantially deplete a planet's atmosphere.
- Students may be interested to know that astronomers believe photoevaporation can also affect whether or not a planet will have moons. Planets very near their host star and/or planets that orbit very hot, bright stars are especially vulnerable to rapid mass loss from photoevaporation, and this mass loss can destabilize the orbits of planets' moons. See this article on AAS Nova for more details.

Big Question Discussion

This lesson should get students thinking about the Big Question "Where do we come from?," in particular, it probes questions about what makes Earth so special. If you choose to delve into the Big Question, consider the following ideas:

- Ask the thought-provoking question, "Of all the places in the universe, why did human life evolve on Earth?" at the beginning of the lesson and recording some of their ideas.
- At the completion of the lesson, return to this question, asking students to cite evidence from the article to support their refined ideas.

Answers

1. While elements as diverse as neon, titanium, and even familiar elements like oxygen and iron have fantastic uses in biology and technology, most of these are exceedingly rare outside of Earth's surface. What elements comprise most of the universe's mass?

Hydrogen and helium comprise 98% of the universe's mass.

2. The Introduction includes an analogy for the fraction of Earth's mass accounted for by its atmosphere.

   a. Explain the analogy.

The fraction of the Earth's mass that is air is analogous to the fraction of the reader's mass that is their pinky fingernail.

   b. What do you think the purpose of the analogy is? Why does the author use it?

The author uses this analogy to help the reader understand how small the mass of air is by making a personal connection to the reader.

3. Summarize and explain **Figure 1.** in the Science Bite in your own words.

The diagram shows how photoevaporation occurs on the molecular level. When a gaseous molecule in the atmosphere is struck by UV radiation it can gain enough energy to escape the gravitational field of Earth.

4. A student describes the process of photoevaporation by saying, “When a molecule in the atmosphere is struck by UV radiation, energy is created, causing the molecule to move much faster.”

a. What is wrong with this description?

Energy is not created in this collision—energy is neither created nor destroyed, it is only transformed from one form to another (first law of thermodynamics).

b. What is a more accurate way to describe the process by which molecules’ kinetic energy increases during the photoevaporation process?

When a molecule absorbs UV radiation some of the energy of electromagnetic radiation is converted to kinetic energy, meaning that the molecule’s velocity increases.

5. “Evaporation” usually means liquid molecules changing to gas molecules. How is the typical definition different from how the term evaporation is used in the Science Bite?

Evaporation in the context of the Bite means a gas in the atmosphere of a planet escapes from the atmosphere to outer space. It is short for “photoevaporation”

6. What are two possible sources of the energy required to cause photoevaporation of molecules in the atmosphere of rocky planets?

UV radiation from stars or from superheated matter that is spiraling into black holes.

7. A common misunderstanding is that heat from the sun warms Earth by conducting heat directly from the sun to the Earth. Using what you learned in the Bite, explain how the sun actually transfers energy to Earth.

Light from the sun is not heat. When the sun’s light reaches Earth and collides with molecules on Earth, those molecules’ kinetic energy increases, meaning that they are warmer. Thus heat results from the conversion of light into molecular kinetic energy not through direct transfer of thermal energy to the Earth from the sun.

8. What is “escape velocity” and why is it important?

Escape velocity is the minimum velocity a molecule needs to photoevaporate. It is important because it determines which molecules remain in the atmosphere and which escape into outer space.

9. The escape velocity of Earth is about 11,000 m/s. A hydrogen molecule has a mass of approximately 1.7×10^{-27} kg. Calculate the minimum kinetic energy a hydrogen molecule needs to photoevaporate. Show your work and include units in your answer.

$KE = ½mv^2 = ½\times1.7\times10^{-27}\text{ kg}\times(11{,}000\text{ m/s})^2 = 1.03\times10^{-16}\text{ J}$

10. Earth is located near the edge of the Milky Way, far from the supermassive black hole at the center of the galaxy. Based on this information and the information from the Science Bite, do you think photoevaporation due to heating from the matter around a supermassive black hole is a significant cause of Earth's thin atmosphere? Support your answer with at least two pieces of evidence.

No, photoevaporation from the supermassive black hole at the center of the Milky Way is unlikely to have been a significant cause of Earth's thin atmosphere. The Earth is too far from the supermassive black hole at the center of the Milky Way for the black hole to have caused a significant amount of photoevaporation. Additionally, the supermassive black hole at the center of the Milky Way doesn't have a lot of superheated matter surrounding it, so it couldn't have caused much photoevaporation.

11. Is the amount of kinetic energy required for an oxygen molecule, which is about 16 times heavier than a hydrogen molecule, to photoevaporate greater than, less than, or equal to the amount needed for a hydrogen molecule to photoevaporate? Justify your choice.

Greater than; Kinetic energy is directly proportional to mass. Thus a heavier molecule moving at the same escape velocity would have more kinetic energy than a lighter molecule.

12. Connect to the Big Question. Would hydrogen or oxygen be more likely to photoevaporate from Earth? Explain how you know. Why is this significant for human life?

Hydrogen. At a given temperature, more hydrogen molecules would attain the escape velocity than would oxygen molecules. Humans depend on oxygen in the atmosphere for life. If oxygen photoevaporated at a much more rapid rate than human life as we know it could not exist on Earth.