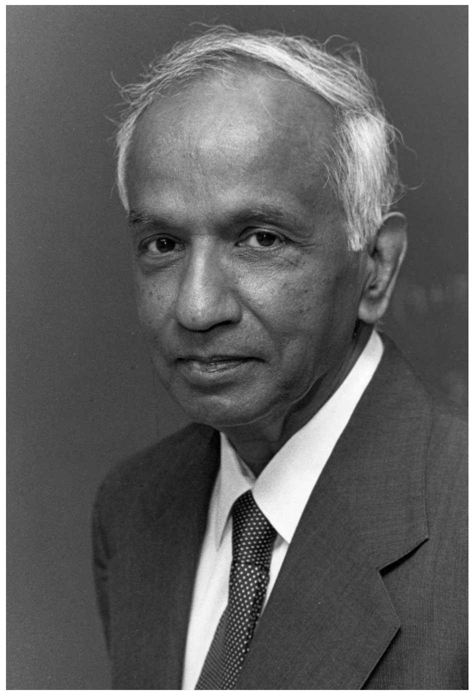
Lesson Plan
Black Holes and Telescopes
Subrahmanyan Chandrasekhar



Grade Level(s):	9-12	Subject(s): Astronomy, History

In-Class Time:	40 to 80 mins	Prep Time: 15 – 20 mins

Materials

- Computer and Internet
- AV equipment
- Printer

Objective

The objective of this lesson is for students to learn about Nobel Laureate, Subrahmanyan Chandrasekhar (known as Chandra) and his influence in astrophysics. Between the two lesson options provided in this Teaching Guide, students should learn about the history of our knowledge of blackholes and/or the Chandra X-Ray Observatory. Chandrasekhar faced controversy early in his career because his mathematics indicated the existence of an object that was unknown at the time. This object we now know is a black hole.

Introduction

Chandrasekhar (Seandra – say – car)

A Nobel Laureate, an immigrant, a suit and tie man, a lover of cornflakes. Subrahmanyan Chandrasekhar, or Chandra, was one of the great physicists of the 20th century. He was a humble man who pursued many different research subjects and valued all the friendships he made in his life. He liked to summarize his own life in two sentences:

> *"I left India and went to England in 1930. I returned to India in 1936 and married a girl who had been waiting for six years, came to Chicago, and lived happily thereafter."* (Cropper, 2004)

Born in 1910 in Lahore, India, Chandra came from a well-to-do family in Madras, India. Chandra's father pressured him to study physics in college, like his uncle, C. V. Raman, who was a Physics Nobel laureate for his discovery of the Raman effect. This describes the behavior of scattered light and how it may change wavelength. Chandra attended Presidency College in Madras, where he studied physics and mathematics. During this time, physicist Arnold Sommerfeld visited Madras. Chandra set up a meeting with him during which Chandra wanted to impress Sommerfeld with his knowledge of physics. Sommerfeld told Chandra that new discoveries had been made since the material he studied was published and it was now all out of date. He then prompted Chandra to focus on the new statistical method he was working on. After some independent studying, Chandra wrote a paper on his application of Sommerfeld's method. Chandra sent his paper to Ralph Fowler. After some suggested edits Fowler deemed Chandra's paper ready to be published. Fowler sent the paper to the *Proceedings of the Royal Society*.

After this publication, Chandra received a scholarship from the Indian Government to attend the University of Cambridge for graduate school. It was difficult decision for Chandra. His mother was ill, and he did not want to leave her. His mother, however, encouraged him to attend Cambridge, knowing that this opportunity would expand his horizons. Chandra left India in July of 1930 by ship. During the trip, Chandra worked. He was curious about the "white dwarf" stars Fowler had written about in a paper published by the *Royal Astronomical Society*. The extreme mass to volume ratio of these stars was what piqued Chandra's interest. Chandra then started on a mathematically different version of Fowler's theory.

On this ship ride, with three textbooks as resources and lengthy calculations to do, Chandra arrived at the conclusion that any star with a mass 1.4 or more times larger than our Sun is too large to create a white dwarf. Instead, the star will collapse on itself. What this collapse would create was unknown at the time and would lead to some controversy in later years. At Cambridge Chandra met Fowler, Dirac, and Eddington. He took their classes and continued to focus his graduate studies on white dwarf stars and their internal structures. Chandra completed his Ph.D. in 1933.

Chandra, running out of his original scholarship money, applied for the Trinity College Fellowship. This would give him a few more years to do research at Cambridge and Trinity. This fellowship was extremely difficult to get and only one Indian man had ever received it before him. Chandra did not expect to get the fellowship and he rented a room in Oxford to go work with his friend Edward Milne. On his way to Oxford Chandra stopped to check the list of fellows—to his surprise, his name was on the list.

At his return to Cambridge, he focused his research on the evolution on stars and how large stars ended their life cycles. In 1934, Chandra finalized his theory of the mass limit of white dwarfs. Eddington took a real interest in Chandra's theory. He stopped by his office two to three times a week, if not every day. This led to them developing a strong friendship. At the end of 1934, Chandra was ready to present his theory to the Royal Society. He was shocked when he saw the program. Eddington was to speak immediately after him on the same topic. Eddington and Chandra did not speak about the meeting at all. After Chandra had presented his theory Eddington started his talk. He opened with,

> *"I do not know whether I shall escape form this meeting alive, but the point of my paper is that there is no such thing as relativistic degeneracy!"* (Cropper, 2004)

Relativistic degeneracy was then the scientific term for Chandra's topic.

When Eddington concluded, the president of the meeting stated, "the argument of this paper will need to be very carefully weighed before we can discuss it." (Cropper, 2004) Eddington's major problem with Chandra's theory was that his mathematics determined that massive stars would collapse into an object of radius zero and with an infinite mass. This was very shocking and unthinkable at the time.
To people today, Eddington's argument against this possibility might be difficult to understand since black holes are now common knowledge and are often featured in sci-fi movies, books, etc.
However, Chandra was upset. He discussed the issue with Eddington, yet no matter how Chandra explained his work Eddington was steadfast in his conclusion that Chandra must have made a mistake. Chandra was able to rally informal support from his mentors Fowler, Dirac, Bohr, and Pauli. His friend Leon Rosenfield assured him that his theory was correct, and he needed to "cheer up." Despite their professional dispute, Eddington and Chandra maintained their friendship. This confused Chandra. Due to a lack of public support for this white dwarf theory Chandra had to move along to a new research subject.

In the winter of 1935, Chandra went to Harvard to lecture for three months. He was then offered two positions, one at Harvard and another at the University of Chicago's Yerkes Observatory. Chandra chose Yerkes, one of the world's leading observatories at the time. Finally feeling settled in a position, Chandra returned to India in the summer of 1936. He was now ready to marry his long-time love, Lalitha. They had met during their undergraduate studies, both studying physics. Lalitha and Chandra married in September of 1936. They moved to the Yerkes Observatory in Williams Bay, Wisconsin in March of 1937, where they resided for 27 years. Chandra developed a graduate program at Yerkes and it quickly became a top astrophysics and astronomy institution. Chandra loved teaching and valued the relationships he developed with his students over his many decades-long career as an educator. In 1952, administrative disputes with colleagues prompted Chandra to leave Yerkes. He found a position in the University of Chicago's Physics department. Chandra formally retired from teaching in 1980 but was present and still on the university payroll until 1985.

In 1983 Chandra won a Nobel Prize, shared with William Fowler, "for his theoretical studies of the physical processes of importance to the structure and evolution of the stars." (NobelPrize.org,

1983) This prize was 50 years after the completion of the research. Because of the conflict with Eddington, Chandra had never received any award up until the Nobel for his work on the white dwarf mass limit. Once Chandra received the Nobel Prize, he was gracious and unfazed. Chandra stated in a 1987 interview,

"I never thought that the recognition that one receives in one's lifetime is a measure of what one is." (Krisciunas, 1987)

Chandra was a person who found his happiness in the pursuit of scientific research-- not the acknowledgement that came from it.

Chandra X-Ray Observatory

The Chandra X-Ray Observatory is one many great observatories. Others include the Hubble Space Telescope, Compton Gamma Ray Observatory, and Spitzer Space Telescope. What sets the Chandra apart is that it detects light beyond the visible spectrum. It detects X-ray radiation, which can be used to detect extremely hot objects. These include material around black holes, exploded stars, and clouds of gas between galaxies.

The Chandra is controlled out of the Smithsonian's Astrophysical Observatory in Cambridge, MA. And this year will be the 20th anniversary of the first deployment of the observatory, in 1999. On July 23rd, the Chandra X-Ray Observatory turns 20! Be sure to keep up with the observatory via its Twitter. The observatory has a very active Twitter that updates a few times a day with what Chandra is observing at that moment.

Instructions

Engage: 5 - 10 Minutes

It is important for students to recall their knowledge on the life cycle of a star for this lesson. Bring back knowledge about the life cycle of our sun and other stars. Important to high light the fact that our sun is a smallish star. Bring up and ask students what they recall from the life cycle of the sun. Critically, how different stars of different masses end their life cycles. Smaller stars end as White Dwarfs, medium stars end up as Neutron Stars and Black Holes.	
What is the teacher doing? Prompt students to recall the life cycle of a star. Ask them about the different ways star's life cycles end.	**What are the students doing?** Listening to teacher. Answering questions.

Explore: 15 Minutes

Bring up how Chandrasekhar was one of the first people to find mathematical proof that there was no limit to the density that can be reached when a massive star dies. Meaning that there is no ultimate type of dead star, not all stars die and turn into other stars. He found this while studying what stars would become white dwarfs. Inform students that when large stars die, they die in violent explosions and the gases that are given off are extremely hot. These gasses are at such high temperatures that the energy levels of the photons in these reactions are above the visible light energy range. These photons are in the X-Ray

range. The earth's atmosphere blocks x-rays so these high energy photons cannot be observed inside the earth's atmosphere.

What is the teacher doing?	**What are the students doing?**
Telling students above information about Chandra and his discovery in 1933. Then talking about when a star collapses into a black hole there is an explosion. These explosions put out very hot gas and scientists are interested in studying this hot gas. Tell students how we can study this hot gas and hot new stars with X-Ray Telescopes. Bring up Chandra X-Ray Observatory. Play video about Observatory (NASA or 15th Anniversary). Hand out Fact Sheet 4 to students for them to take notes on. (Found below in Required Resources, courtesy Harvard, Chandra X-Ray Observatory)	Students will be listening to the teacher. Students will watch video. Students will read and take notes on the fact sheets about Chandra X-Ray Observatory.

Explain: 10 Minutes

This is a good time to cover any questions students might have about the telescope or Chandrasekhar.

What is the teacher doing?	**What are the students doing?**
Answer any questions. Lead this into a talk about the partnership between the four Great Observatories and how they allow us to see a more complete picture of the universe.	Asking questions. Taking notes.

Elaborate: 5 Minutes

This is the fun part! The Chandra Observatory has a very active Twitter account. It would be fun for students to get a chance to explore this and find their favorite picture posted by the Observatory team. If possible, have students explore the Twitter account on their own devices. If not have teacher project Twitter account and take a few minutes to find a picture that is the classes favorite.

What is the teacher doing?	**What are the students doing?**
Looking through Twitter account	Looking through Twitter account

Alternative Explore: 30 Minutes

Something that might the hard to imagine for students today is the fact that no one believed Chandra partially because his math lead to the conclusion that there must be some object that's radius goes to zero and mass goes to infinity. This object is what we know as a black hole, but prior to the 1950s no one dare publish anything speculating what these objects might be.

What is the teacher doing?	What are the students doing?
Present the Britannia video on Chandrasekhar. Tell students about how no one believed Chandra's white dwarf theory because his math lead to massive stars ending their life to be a black hole. Split students into three groups (for large classes 6 and divide time frame in half) Assign each group to research the major discoveries about black holes. First group researches from 1750 to 1970 Second group researches from 1970 to 2000 Third group researches from 2000 to 2020 Present students with the resources appropriate for their time period.	Watching video. Listening to teacher. Exploring resources for their time period and doing research. Creating a presentation using the appropriate resources available in their classroom.

Alternative Explain: 10 - 15 Minutes

Students should present the information they found in their research to share with the class	
What is the teacher doing? Watching students present their research. Making sure everything is correct.	**What are the students doing?** Presenting their research or listening to other students' presentations. Student presentations should only be approximately three minutes

Alternative Elaborate: 10 Minutes

While talking about black holes bring the discussion around to how we observe black holes today. The first ever picture taken of a black hole used radio telescopes. One of the telescopes that can see black holes is the Chandra X-Ray Observatory. Named after Dr. Chandra for his great impact in astrophysics and astronomy.	
What is the teacher doing? Talk about how we can observe black holes with the very special Chandra X-Ray Observatory. Bring up the first image of a black hole. Bring up Chandra's image of the black hole. If time let students check out the Twitter account of the Chandra X-Ray Observatory.	**What are the students doing?** Students will look at pictures of the black hole. Student then will look through the Chanda X-Ray Observatory's Twitter account and find their favorite picture from space.

Evaluate:

Have students complete Discussion Questions. Evaluate as necessary

Required/Recommended Reading and Resources

NASA Video about Chandra X-Ray Observatory
https://youtu.be/2Zc1jTN09C8

Fact Sheet 4 about Chandra X-Ray Observatory
http://chandra.harvard.edu/graphics/press/fact4-print.pdf

Chandra X-Ray Observatory website
http://chandra.harvard.edu/edu/

15th Anniversary Video about Chandra X-Ray Observatory
https://www.youtube.com/watch?v=DfJmBOA_gMQ

Britannica Video about Chandrasekhar and black holes
https://www.britannica.com/biography/Subrahmanyan-Chandrasekhar

Timeline of the History of Black Holes, best for years 1700 till 1970
http://blackholes.stardate.org/history.html

Timeline of the History of Black Holes, best for 1970 post
https://www.sciencenewsforstudents.org/article/short-history-of-black-holes

Discussion Questions

Discussion Questions can be found as a Handout with a corresponding Answer Key in the Supplemental Materials to this lesson plan.

1. What year did Chandrasekhar move to England?
    a) 1930
2. How many universities did Chandrasekhar work for?
    a) One, University of Chicago.
    b) He attended: Presidency College, Cambridge, and Trinity
    c) He lectured at Harvard for a few months before going to Chicago's Yerkes Observatory
3. How did the conflict with Eddington affect Chandrasekhar's career? What sparked the conflict?
    a) He didn't get the Nobel until decades later for something he should have gotten in the 1940s
    b) He had to move on to a different research area
    c) Eddington could not believe Chandra's math because it led to an object of radius zero and infinite mass
4. Who coined the term "black holes"? When did this happen?
    a) John Wheeler
    b) At a NASA conference in December 1967?
5. What company published the first article about black holes?
    a) Science News Letter now Science News

6. When was the Chandra X-Ray Observatory launched?
    a) July 23rd, 1999
7. What are the main uses of the Chandra X-Ray Observatory?
    a) To observe hot gases, exploding stars, and young stars that have very active surfaces
    b) Space material that is too hot to be seen with visible light
    c) To observe supernovas
8. What is the mass limit of a White Dwarf? What is the mass limit of a Black Hole?
    a) 1.4 solar masses or less a star dies as a White dwarf
    b) 8 or more solar masses a star dies as a Black hole
9. How does the Chandra X-Ray Observatory detect black holes?
    a) The observatory detects the super-hot gas and dust that is swirling around the black hole.
10. How often do Supernova occur?
    a) About every fifty years in our galaxy
11. When was the first picture of a black hole taken? What type of telescope was it taken with?
    a) 2019
    b) Radio Telescopes
12. What elements are created in a Supernova?
    a) Gold
    b) Titanium
    c) Uranium
13. How long did Chandrasekhar work at Yerkes Observatory?
    a) 15 years
14. Why are scientists interested in studying young stars?
    a) Because scientists would like to understand how when our sun was young the sun flares effected the Earth
15. Why do we have to use satellites to observe the X-Rays from space?
    a) Earth's atmosphere absorbs X-Rays so we can't detect this data on earth's surface.

Further Reading and Additional Resources

AIP Oral History Interview with Chandrasekhar
https://www.airspacemag.com/how-things-work/how-things-work-chandra-x-ray-23580481/

Some more about the history of black holes
https://www.sciencenews.org/blog/context/50-years-later-its-hard-say-who-named-black-holes

List of the Great Observatories
https://www.nasa.gov/audience/forstudents/postsecondary/features/F_NASA_Great_Observatories_PS.html

Chandra X-Ray Observatory Turns 20

http://chandra.harvard.edu/20th/

Chandra Takes captures an image of the first pictured Black Hole
https://www.space.com/1st-black-hole-photo-x-ray-neighborhood-views.html

Chandra's Role in 20th century Science
https://physicstoday.scitation.org/doi/10.1063/1.3529001

The Nobel Prize in Physics 1983. NobelPrize.org. Nobel Media AB 2019. Mon. 24 Jun 2019.
https://www.nobelprize.org/prizes/physics/1983/summary/

Interview of S. Chandrasekhar by Kevin Krisciunas on 1987 October 6,
Niels Bohr Library & Archives, American Institute of Physics,
College Park, MD USA,
www.aip.org/history-programs/niels-bohr-library/oral-histories/4552

Interview of S. Chandrasekhar by Spencer Weart on 1977 May 17,
Niels Bohr Library & Archives, American Institute of Physics,
College Park, MD USA,
www.aip.org/history-programs/niels-bohr-library/oral-histories/4551-1

Srinivasan, G., & Penrose, R. (1999). From White Dwarfs to Black Holes

Cropper, W. (2004). Great physicists (pp. 438-451).

Physics Today **63**, 12, 49 (2010); https://doi.org/10.1063/1.3529002 Some memories of Chandra

Physics Today 63, 12, 44 (2010); https://doi.org/10.1063/1.3529001 Chandrasekhar's role in 20th-century science

Extensions

- N/A

Common Core Standards

For more information on Common Core Standards, visit http://www.corestandards.org/.

Reading: Informational Text	
CCSS.ELA-LITERACY.RI.9-10.1	Cite strong and thorough textual evidence to support analysis of what the text says explicitly as well as inferences drawn from the text.
CCSS.ELA-LITERACY.RI.9-10.2	Determine a central idea of a text and analyze its development over the course of the text, including how it emerges and is shaped and refined by specific details; provide an objective summary of the text.

CCSS.ELA-LITERACY.RI.9-10.6	Determine an author's point of view or purpose in a text and analyze how an author uses rhetoric to advance that point of view or purpose.
CCSS.ELA-LITERACY.RI.9-10.10	By the end of grade 9, read and comprehend literary nonfiction in the grades 9-10 text complexity band proficiently, with scaffolding as needed at the high end of the range. By the end of grade 10, read and comprehend literary nonfiction at the high end of the grades 9-10 text complexity band independently and proficiently.
CCSS.ELA-LITERACY.RI.11-12.1	Cite strong and thorough textual evidence to support analysis of what the text says explicitly as well as inferences drawn from the text, including determining where the text leaves matter uncertain.
CCSS.ELA-LITERACY.RI.11-12.2	Determine two or more central ideas of a text and analyze their development over the course of the text, including how they interact and build on one another to provide a complex analysis; provide an objective summary of the text.
CCSS.ELA-LITERACY.RI.11-12.6	Determine an author's point of view or purpose in a text in which the rhetoric is particularly effective, analyzing how style and content contribute to the power, persuasiveness or beauty of the text.
CCSS.ELA-LITERACY.RI.11-12.10	By the end of grade 11/12, read and comprehend literary nonfiction in the grades 11-CCR text complexity band proficiently, with scaffolding as needed at the high end of the range.
Speaking & Listening	
CCSS.ELA-LITERACY.SL.9-10.1.B	Work with peers to set rules for collegial discussions and decision-making (e.g., informal consensus, taking votes on key issues, presentation of alternate views), clear goals and deadlines, and individual roles as needed.
CCSS.ELA-LITERACY.SL.9-10.2	Integrate multiple sources of information presented in diverse media or formats (e.g., visually, quantitatively, orally) evaluating the credibility and accuracy of each source.
CCSS.ELA-LITERACY.SL.9-10.4	Present information, findings, and supporting evidence clearly, concisely, and logically such that listeners can follow the line of reasoning and the organization, development, substance, and style are appropriate to purpose, audience, and task.
CCSS.ELA-LITERACY.SL.9-10.5	Make strategic use of digital media (e.g., textual, graphical, audio, visual, and interactive elements) in presentations to enhance understanding of findings, reasoning, and evidence and to add interest.
CCSS.ELA-LITERACY.SL.9-10.6	Adapt speech to a variety of contexts and tasks, demonstrating command of formal English when indicated or appropriate. (See grades 9-10 Language standards 1 and 3 here for specific expectations.)

CCSS.ELA-LITERACY.SL.11-12.1.B	Work with peers to promote civil, democratic discussions and decision-making, set clear goals and deadlines, and establish individual roles as needed.
CCSS.ELA-LITERACY.SL.11-12.2	Integrate multiple sources of information presented in diverse formats and media (e.g., visually, quantitatively, orally) in order to make informed decisions and solve problems, evaluating the credibility and accuracy of each source and noting any discrepancies among the data.
CCSS.ELA-LITERACY.SL.11-12.4	Present information, findings, and supporting evidence, conveying a clear and distinct perspective, such that listeners can follow the line of reasoning, alternative or opposing perspectives are addressed, and the organization, development, substance, and style are appropriate to purpose, audience, and a range of formal and informal tasks.
CCSS.ELA-LITERACY.SL.11-12.5	Make strategic use of digital media (e.g., textual, graphical, audio, visual, and interactive elements) in presentations to enhance understanding of findings, reasoning, and evidence and to add interest.
CCSS.ELA-LITERACY.SL.11-12.6	Adapt speech to a variety of contexts and tasks, demonstrating a command of formal English when indicated or appropriate. (See grades 11-12 Language standards 1 and 3 here for specific expectations.)
History/Social Studies	
CCSS.ELA-LITERACY.RH.9-10.1	Cite specific textual evidence to support analysis of primary and secondary sources, attending to such features as the date and origin of the information.
CCSS.ELA-LITERACY.RH.9-10.2	Determine the central ideas or information of a primary or secondary source; provide an accurate summary of how key events or ideas develop over the course of the text.
CCSS.ELA-LITERACY.RH.9-10.10	By the end of grade 10, read and comprehend history/social studies texts in the grades 9-10 text complexity band independently and proficiently.
CCSS.ELA-LITERACY.RH.11-12.1	Cite specific textual evidence to support analysis of primary and secondary sources, connecting insights gained from specific details to an understanding of the text as a whole.
CCSS.ELA-LITERACY.RH.11-12.2	Determine the central ideas or information of a primary or secondary source; provide an accurate summary that makes clear the relationships among the key details and ideas.
CCSS.ELA-LITERACY.RH.11-12.10	By the end of grade 12, read and comprehend history/social studies texts in the grades 11-CCR text complexity band independently and proficiently.
Science & Technical Subjects	
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.

CCSS.ELA-LITERACY.RST.9-10.2	Determine the central ideas or conclusions of a text; trace the text's explanation or depiction of a complex process, phenomenon, or concept; provide an accurate summary of the text.
CCSS.ELA-LITERACY.RST.9-10.4	Determine the meaning of symbols, key terms, and other domain-specific words and phrases as they are used in a specific scientific or technical context relevant to *grades 9-10 texts and topics*.
CCSS.ELA-LITERACY.RST.9-10.6	Analyze the author's purpose in providing an explanation, describing a procedure, or discussing an experiment in a text, defining the question the author seeks to address.
CCSS.ELA-LITERACY.RST.9-10.10	By the end of grade 10, read and comprehend science/technical texts in the grades 9-10 text complexity band independently and proficiently.
CCSS.ELA-LITERACY.RST.11-12.1	Cite specific textual evidence to support analysis of science and technical texts, attending to important distinctions the author makes and to any gaps or inconsistencies in the account.
CCSS.ELA-LITERACY.RST.11-12.2	Determine the central ideas or conclusions of a text; summarize complex concepts, processes, or information presented in a text by paraphrasing them in simpler but still accurate terms.
CCSS.ELA-LITERACY.RST.11-12.4	Determine the meaning of symbols, key terms, and other domain-specific words and phrases as they are used in a specific scientific or technical context relevant to *grades 11-12 texts and topics*.
CCSS.ELA-LITERACY.RST.11-12.6	Analyze the author's purpose in providing an explanation, describing a procedure, or discussing an experiment in a text, identifying important issues that remain unresolved.
CCSS.ELA-LITERACY.RST.11-12.10	By the end of grade 12, read and comprehend science/technical texts in the grades 11-CCR text complexity band independently and proficiently.

Next Generation Science Standards

For more information on the Next Generation Science Standards, visit http://www.nextgenscience.org/.

Dimension One: Practices	1. Asking questions (for science) 3. Planning and carrying out investigations 8. Obtaining, evaluating, and communicating information
Dimension Two: Crosscutting Concepts	1. Systems and system models 2. Energy and matter: Flows, cycles, and conservation 3. Structure and function
Dimension Three: Disciplinary Core Ideas	ESS1.A, PS1.B, PS3.A