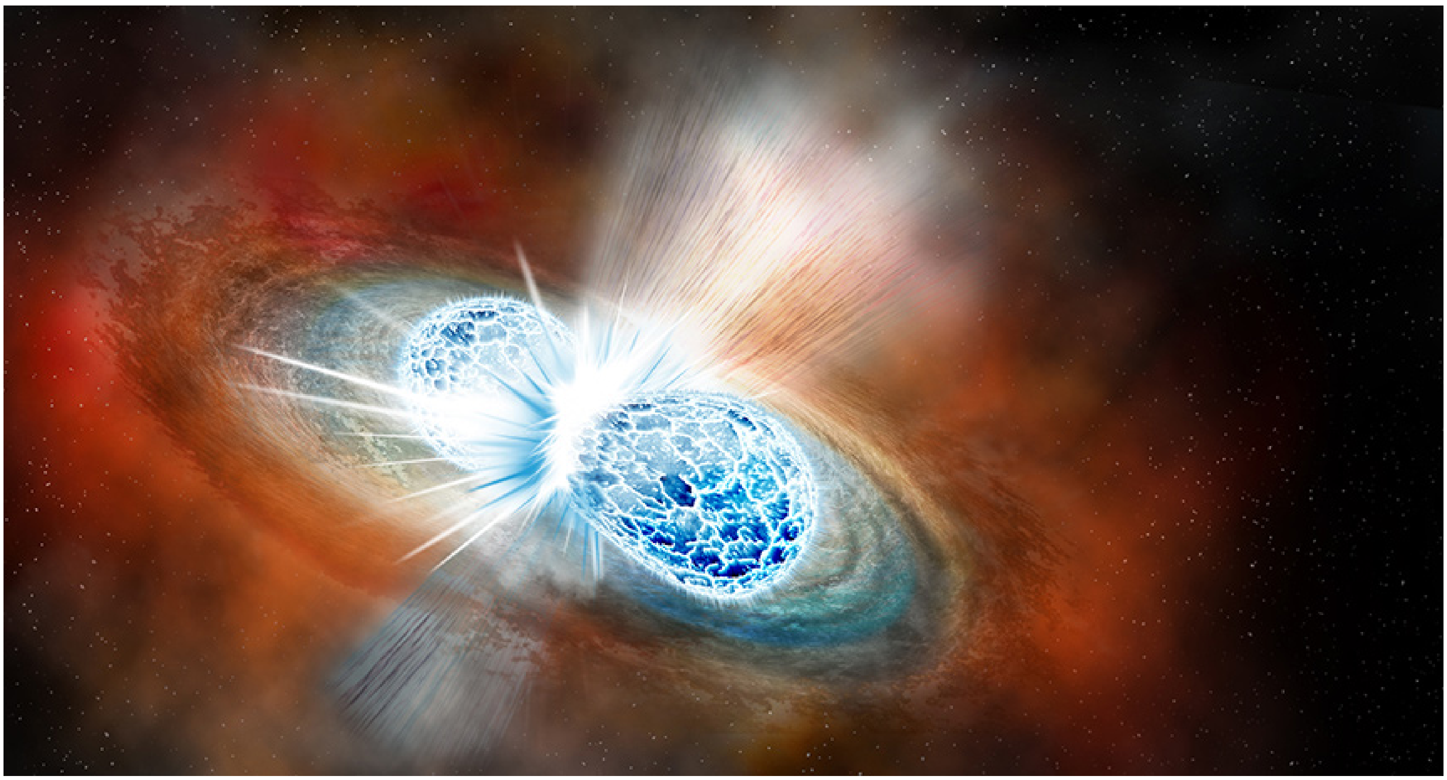
Science News

IN HIGH SCHOOLS | EDUCATOR GUIDE



ROBIN DIENEL, COURTESY OF CARNEGIE INSTITUTION FOR SCIENCE

November 11, 2017

Neutron Star Crash Seen for First Time

SOCIETY FOR SCIENCE & THE PUBLIC

SN EDUCATOR GUIDE

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About the Issue

***Science News* article(s):** "Neutron star crash seen for first time"

Readability score: 11.7

***Science News for Students* article(s):** "Astronomers finally find the cosmic source of gold and silver"

Readability score: 8.1

The article "Neutron star crash seen for first time" describes how, for the first time, astrophysicists have observed two neutron stars colliding as well as signs that the collision produced heavy metal elements. Students can focus on details reported in the article, follow connections to earlier articles about black hole collisions and gravitational waves and explore cross-curricular connections to other major science topics in physics, chemistry and engineering. In a related activity, students can calculate some of the physical conditions involved in star and element formation.

Before beginning any part of this guide, be sure to watch the video "Light and gravitational waves reveal a neutron star crash" (scroll down to find the video at the end of the article), which provides an overview of the observations that led scientists to determine that a neutron star collision occurred and was witnessed for the first time. You could also start off with a gravitational wave lesson, so students have a better understanding of what gravitational waves are and how they are measured. The Making Waves Educator Guide links to several *Science News* and *Science News for Students* articles and has many guided questions and a relevant interferometer activity.

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What's in This Guide?

Article-based observation: Questions focus on how scientists observed and identified the neutron star collision and what they learned from the collision.

Quest through the archives: Use this short section to explore other articles about collisions in space and gravity waves as reported by *Science News* since 1924.

Cross-curricular discussion:

> **Chemical Sciences** questions address the principles of spectroscopy and how spectroscopy is used in astronomy to understand element production and elemental properties.
>
> **Physical Sciences** questions concern stellar evolution and reactions.
>
> **Engineering and Experimental Design** questions deal with theoretical calculations related to visiting another galaxy and various applications for the technologies discussed in the article.

Activity: The Pressure to Be a Star

> **Purpose:** To understand the lifecycle of stars and how stars produce various elements.
>
> **Procedural overview:** Students can use basic algebra, physics and chemistry principles to estimate the conditions involved in stars and element formation.
>
> **Approximate class time:** 30-50 minutes.

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Standards

Next Generation Science	Common Core ELA
Matter and its Interactions: HS-PS1-1, HS-PS1-2, HS-PS1-3, HS-PS1-5, HS-PS-1-8	Reading Informational Text (RI): 1, 2, 4, 5, 7
Motion and Stability: Forces and Interactions: HS-PS2-1, HS-PS2-4	Writing (W): 1, 2, 3, 4, 6, 7, 8, 9
Energy: HS-PS3-1, HS-PS3-2, HS-PS3-5	Speaking and Listening (SL): 1, 2, 4, 5, 6
Waves and their Applications in Technologies for Information Transfer: HS-PS4-1, HS-PS4-5	Reading for Literacy in Science and Technical Subjects (RST): 1, 2, 3, 4, 5, 7, 8, 9
Earth's Place in the Universe: HS-ESS1-1, HS-ESS1-2, HS-ESS1-3, HS-ESS1-4	Writing Literacy in History/Social Studies and Science and Technical Subjects (WHST): 1, 2, 4, 7, 8, 9
Engineering Design: HS-ETS1-1, HS-ETS1-2, HS-ETS1-3	

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Article-Based Observation: Q&A

Based on the article "Neutron star crash seen for first time":

1. This article summarizes breaking news in the world of science. Create a Snapchat post that summarizes the article to share with your friends.

Possible student response: Draw your own image of a neutron star collision (you can refer to the guide cover image for inspiration) and add text such as "Two neutron stars collide!" Label the electromagnetic waves and gravitational waves being emitted. Create stamps of different heavy metal elements and place them on the image so they appear to be emitted from the crash.

2. What is a neutron star? How massive were the neutron stars that collided?

Possible student response: A neutron star is an ultradense, neutron-rich core of a dead star. When some stars grow old they explode and the elements within it compress. The neutron stars had masses between 1.17 and 1.60 times that of the sun.

3. Where were gravitational waves from the neutron star collision detected?

Possible student response: Gravitational waves were detected by the Advanced Laser Interferometer Gravitational-Wave Observatory (LIGO) in Louisiana and Washington state. In both locations, LIGO detected a burst of approximately 100 seconds of gravitational waves, the strongest and longest signal yet detected. Only a faint gravitational wave signal was recorded by LIGO's sister experiment in Italy, Advanced Virgo.

4. How did scientists determine the direction from which the gravitational waves came? Where were the colliding neutron stars located?

Possible student response: Gravitational wave detectors are more sensitive to gravity waves coming from certain directions relative to the orientation of the detector. With three gravitational wave detectors (two LIGO detectors plus the Virgo detector in Italy), scientists can compare the gravitational wave signals arriving at each detector to determine which direction the waves came from. LIGO's two detectors in the United States sensed a strong signal, but the Virgo detector in Italy only sensed a weak signal, indicating that the waves came from a certain area of the sky to which Virgo is not very sensitive. A new speck of glowing visible light in that area of the sky glimpsed by telescopes, helped scientists pinpoint the colliding stars' location: galaxy NGC 4993, 130 million light-years from Earth in the constellation Hydra.

5. What corresponding electromagnetic radiation was detected from the neutron star collision?

Possible student response: Just 1.7 seconds after LIGO received the gravitational wave signal, NASA's Fermi space telescope detected gamma rays in the same region of the sky. Other telescopes spotted a glow of visible and infrared light starting about 11 to 12 hours after the collision. More than a week later, as those wavelengths faded away, X-rays were emitted, followed by radio waves.

6. How did scientists conclude that the colliding celestial bodies were neutron stars and not black holes?

Possible student response: Black holes that scientists had previously recorded merging were much more massive — tens of times the mass of the sun — than the crashing bodies that were recorded in this merger. Also, the recent collision emitted various types of light. A black hole collision is not expected to produce light. Both of these observations led scientists to determine that the colliding celestial bodies were neutron stars and not black holes.

7. What elements were produced by the neutron star collision, and by what process? What was significant about this discovery?

Possible student response: The collision produced heavy elements including gold (about 10 to 100 times the Earth's mass in gold!), silver, platinum and uranium. In a chain of reactions called the r-process, atomic nuclei combine with neutrons and undergo radioactive decay, transforming into new elements. Astrophysicists had never directly witnessed the r-process or the creation of these heavy metal elements, and debated whether the r-process occurred in supernovas or neutron star mergers. Though researchers can't yet say whether or not the r-process also occurs in supernovas, scientists now know that when neutron stars collide, a large amount of heavy metal elements are produced via the r-process.

8. What did astrophysicists learn about short gamma-ray bursts? Why is this discovery significant?

Possible student response: The colliding neutron stars emitted a burst of high-energy light called short gamma rays. Similar short gamma-ray bursts are detected about 50 times a year, so it now appears that those come from neutron star collisions too. Up until this recent merger, scientists were uncertain of where short gamma-ray bursts came from.

9. How did astrophysicists use their observations of the neutron star collision to learn more about the expansion of the universe?

Possible student response: By measuring the distance of the collision using gravitational waves and comparing that with how much the universe expansion stretched light from the neutron stars' galaxy, astrophysicists measured the expansion rate of the universe. Scientists previously measured this property, known as the Hubble constant, through other means. But they got two different results: 67 and 73 kilometers per second per megaparsec. The new measurement indicates that distantly separated galaxies are spreading apart at about 70 km/s per megaparsec, right in the middle of the two previous results. Future detections of neutron star mergers could improve the measurement.

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Article-Based Observation: Q&A

Directions: Read the article "Neutron star crash seen for first time," and then answer these questions.

1. This article summarizes breaking news in the world of science. Create a Snapchat post that summarizes the article to share with your friends.

2. What is a neutron star? How massive were the neutron stars that collided?

3. Where were gravitational waves from the neutron star collision detected?

4. How did scientists determine the direction from which the gravitational waves came? Where were the colliding neutron stars located?

5. What corresponding electromagnetic radiation was detected from the neutron star collision?

6. How did scientists conclude that the colliding celestial bodies were neutron stars and not black holes?

7. What elements were produced by the neutron star collision, and by what process? What was significant about this discovery?

8. What did astrophysicists learn about short gamma-ray bursts? Why is this discovery significant?

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Quest Through the Archives: Q&A

1. The article described the latest detection of gravitational waves by LIGO. Can you find an article about the first detection of gravitational waves by LIGO? What is a difference between the recent detection and the first detection of gravitational waves?

Possible student response: The article "Year in review: Gravitational waves offer new cosmic views," published 12/24/2016, recounts how gravitational waves were directly detected for the first time in 2015 and announced to the world in 2016, after having been predicted by Albert Einstein's theory of general relativity nearly a century earlier. The first detected gravitational waves came from the collision of two black holes, and the most recent detection was generated from a neutron star merger. The article about the first detection also describes how observing gravitational waves could tell us more about orbiting black holes, explosions of stars and other cosmic events that create sufficiently strong gravitational waves.

2. Although we cannot mimic neutron star collisions on Earth, we can at least smash heavy nuclei such as gold together at high speeds. Can you find an article about such experiments and what they discovered?

Possible student response: The article "Smashing gold ions creates most swirly fluid ever," published 3/4/2017, discusses how the Relativistic Heavy Ion Collider at Brookhaven National Laboratory in New York accelerated beams of positively charged gold ions to nearly the speed of light and then smashed them together in head-on collisions. During the collisions, the neutrons and protons from the gold break down into their component quarks and gluons, creating a soup called quark-gluon plasma. This plasma was similar to the state of the early universe just millionths of a second after the Big Bang, when it was still too hot for these elementary particles to condense to form neutrons and protons. Among other exotic properties, the quark-gluon plasma created at Brookhaven had a swirliness, or vorticity, measured at 9 billion trillion radians per second. For comparison, the core of a strong tornado has a swirliness of 0.1 radian per second.

3. Can you find an article about an earlier neutron star collision?

Possible student response: The article "Gold seen in neutron star collision debris," published 7/22/2013, discusses how the remnants of a different neutron star collision were indirectly observed in June 2013. No gravitational waves were detected from that collision, but NASA's Swift satellite detected gamma rays from the collision and the Hubble Space Telescope detected visible light. The gamma-ray data showed that the collision produced a gamma-ray burst, similar to the one reported by the most recent neutron star merger. The visible light spectra showed that the collision produced an assortment of heavy elements, including gold, lead, platinum and uranium, but the scientists weren't able to say whether or not the light was produced from the gamma-ray burst or the star collision.

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Quest Through the Archives: Q

Directions: After reading the article "Neutron star crash seen for first time," log in to your *Science News* in High Schools account and use the Search page to answer these questions. Make sure you adjust the filters to include articles written before 1999, if the question requires you to do so.

1. The article described the latest detection of gravitational waves by LIGO. Can you find an article about the first detection of gravitational waves by LIGO? What is a difference between the recent detection and the first detection of gravitational waves?

2. Although we cannot mimic neutron star collisions on Earth, we can at least smash heavy nuclei such as gold together at high speeds. Can you find an article about such experiments and what they discovered?

3. Can you find an article about an earlier neutron star collision?

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Neutron Star Crash Seen for First Time

Cross-Curricular Discussion: Q&A

Directions: After students have had a chance to review the article "Neutron star crash seen for first time," lead a classroom discussion based on the questions that follow.

CHEMICAL SCIENCES

Discussion questions:

1. How can different wavelengths of light be separated to study the spectrum (spectroscopy) of an object in space?

When electromagnetic radiation passes from air (or the vacuum of space) into a prism — including ones found in telescopes — the higher density of the prism causes the light waves to slow and bend. The refraction separates the various wavelengths of light, which causes the separated light waves to leave the prism at slightly different angles. Similarly, light of different wavelengths passing through a diffraction grating is bent by varying degrees depending on the wavelength. This is called dispersion due to diffraction, and happens because the different wavelengths of light interact differently with vertical bars in diffraction grating, which have a fixed spacing comparable to some wavelengths of light. Both refraction and diffraction are used in spectroscopy.

2. How can spectroscopy be used to determine the chemical composition of stars, colliding neutron stars, nebulae (gas clouds) or other objects in space?

Spectroscopy measures electromagnetic radiation (including infrared, ultraviolet, visible light, x-rays and gamma rays) that is emitted, absorbed or scattered by various materials. All elements absorb and emit radiation at specific energies, which result in radiation patterns unique to each element. Those patterns act as a sort of fingerprint, and can help scientists identify and quantify the chemical composition of objects in space.

For more information on spectroscopy in astronomy, see for example:

Guide to Spectroscopy and Spectral Lines
Astronomy Tools: Spectroscopy
Examples of Spectroscopy in Astronomy

Extension prompts:

3. The curve of binding energy shows how tightly bound the nucleons (protons and neutrons) are within a nucleus, depending on the mass of the nucleus. Based on a binding energy curve, similar to the one titled "Fission and fusion can yield energy" found on the HyperPhysics page hosted by Georgia State University, what element appears to have the most stable nucleus? How do you know from the graph?

Iron has the most stable nucleus. All isotopes of iron have the most tightly bound nucleons, meaning they have the highest binding energy per nuclear particle (as this graph shows, the binding energy per nucleon is around 8.8 million electron volts (MeV) for nuclei with masses of about 55 to 60 atomic mass units). It is important to note that nickel-62 actually has the most stable nucleus, but it is not as abundant in stellar cores as iron-56, so astrophysicists use iron to focus their reasoning and explanations.

4. Fusion reactions join small nuclei together to create larger nuclei. Based on that graph, would fusion reactions that produce nuclei that are less massive than iron consume or release net energy?

Fusion reactions that produce nuclei up to iron's atomic mass can release net energy. The protons and neutrons in the initial smaller nuclei are more weakly bound, but they become more strongly bound in the larger nuclei. That difference in their binding energy is released as net energy in the reaction — the reaction is exothermic.

5. Based on that graph, would fusion reactions that result in nuclei that are more massive than iron consume or release net energy?

Fusion reactions can also produce nuclei larger than iron. But those large nuclei have more weakly bound protons and neutrons, so producing such nuclei consumes a great deal of energy — the reaction is endothermic. The energy demands are why heavy elements are mainly only created in high-energy events, such as the collision of neutron stars or during supernovas.

6. For a given mass of fuel, which releases more energy — fusion of very light elements to form a stable nuclei, or fission of a very heavy element to form stable nuclei? Use the graph.

Fission of a heavy element such as ^{235}U *all the way to the most stable element (iron-56) would release roughly 1 MeV per nucleon. Fusion of very light elements, such as hydrogen, all the way to the most stable element (iron-56) would release over 8 MeV per nucleon. Thus, fusion reactions produce much more energy than fission for a given mass of fuel.*

PHYSICAL SCIENCES

Discussion questions:

1. How does a star form?

A protostar is a cloud of mostly hydrogen that contracts and heats up due to gravitational forces to form a star. Fusion reactions called proton-proton reactions, which occur during fusion, become important once the central temperature rises to about $T_c = 8 \times 10^6$ *K. If the protostar has a sufficiently large mass, it will contract until the central temperature is hot enough to produce fusion reactions, and a star will be born.*

2. How does a star live?

Stars rely on fusion to survive. In one type of fusion reaction, the heat and pressure at the center of a star are so great that hydrogen reacts to become helium. In a series of proton-proton, or pp, reactions, four protons are progressively joined together to form helium-4 nuclei called alpha particles. Along the way, two of the protons undergo inverse beta decay to become neutrons. Energy from those fusion reactions maintain the heat and pressure in the core, pushing outward and counterbalancing the inward pull of gravity.

Because both the temperature and the density decrease with radius, almost all of the fusion occurs in the core of the star (provided that unburned fuel remains there).

3. How does a star die?

Toward the end of its life, after a star has consumed most of the hydrogen in its core, the core collapses and heats up the rest of the star until it is hot enough to fuse the hydrogen that remains in the star's mantle; this is called shell burning. The fusion reactions in the mantle cause the surface layers of the star to expand and cool, resulting in an enormous red giant star. Further contraction and heating of the core can lead to the fusion of helium and progressively heavier elements.

In these final stages of fuel consumption, a star often sheds its outer layers. The remaining stellar core collapses to form one of three objects, depending on the star's mass:

a. White dwarf. For stars with masses comparable to our sun or smaller stars, the star contracts until the only thing keeping it from collapsing into a black hole is the fact that its electrons cannot share a quantum state, which is known as electron degeneracy pressure. That pressure stabilizes it, forming a white dwarf that slowly radiates away its residual energy.

b. Neutron star. For stars with masses somewhat larger than our sun, gravity overcomes the degenerate electron pressure at the white dwarf stage. As the star goes supernova (explodes), its core continues to contract until it squeezes its protons and electrons together to form neutrons. The resulting neutron star acts like a giant nucleus of neutrons and is stopped from further collapse by the neutron degeneracy pressure. Eventually the neutrons become so close that they would need to share a quantum state to get any closer, too.

c. Black hole. If the mass of a star is several times larger than that of our sun, gravity overcomes the neutron degeneracy pressure at the neutron star stage and the star collapses, becoming a black hole. Nothing — not even light — that ventures close enough can resist being sucked in by the extreme gravitational field.

Extension prompts:

4. What is a Hertzsprung-Russell diagram?

Hertzsprung-Russell diagrams plot how much light a star produces, called stellar luminosity, versus the star's surface temperature (related to a star's color — redder is cooler and bluer is hotter). Most stars in the universe, including Earth's sun, spend a majority of their life spans on the main sequence, a distinct band of stars on the Hertzsprung-Russell diagram. After consuming most of their fusion fuel, these stars move off the main sequence. What happens to them next depends on their initial masses: stars up to 10 solar masses become red giants, while stars below 0.2 solar masses become white dwarfs. Eventually, all stars collapse when all of the fuel is exhausted.

ENGINEERING AND EXPERIMENTAL DESIGN

Discussion questions:

1. How long did it take light and gravitational waves to travel from the neutron star collision to Earth? How long ago did the collision actually happen?

Scientists determined that the neutron star collision occurred in the galaxy NGC 4993, 130 million light-years from Earth in the constellation Hydra. A light-year is the distance that light travels in a year, so the collision must have occurred approximately 130 million years ago if we are just now seeing light produced from it.

2. The New Horizons probe that flew by Pluto in 2015 is traveling away from our solar system at approximately 52,000 kilometers per hour. What fraction of light speed is that? If New Horizons were traveling toward NGC 4993 and kept that same velocity, how long would it take to reach from Earth whatever is left of the neutron star collision?

New Horizons is traveling at approximately 1/20,800 or 0.0000481 times the speed of light. It would take the probe about 2.7 trillion years to reach the approximate location of the recently detected neutron star collision.

Extension prompts:

3. What sorts of things could we monitor or learn from satellites with similar sensors that are pointed inward toward Earth instead of outward toward space?

Satellites that detect infrared light could tell us information about water, land and air temperatures as well as fires and explosions. Satellites that detect X-rays and gamma rays could tell us information about above-ground nuclear tests. Satellites that detect radio waves could monitor communications.

4. How might the gravitational wave detectors be improved?

If the interferometers had longer arms, the detectors could be more sensitive. If there were more detectors watching at the same time, it would be easier to triangulate the position of the gravitational waves' source in the sky. If some of the detectors were in space, they could help to better eliminate sources of Earth-based noise from the signals. Space-based detectors could also measure gravitational waves from different sources, like colliding supermassive black holes, which emit gravitational waves at longer wavelengths.

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Cross-Curricular Discussion: Q

Directions: The following list of discussion questions is provided to help you take notes, brainstorm ideas and test your thinking in order to be more actively engaged in class discussions related to this article. All questions in this section are related to topics covered in "Neutron star crash seen for first time."

CHEMICAL SCIENCES

Discussion questions:

1. How can different wavelengths of light be separated to study the spectrum (spectroscopy) of an object in space?

2. How can spectroscopy be used to determine the chemical composition of stars, colliding neutron stars, nebulae (gas clouds) or other objects in space?

Extension prompts:

3. The curve of binding energy shows how tightly bound the nucleons (protons and neutrons) are within a nucleus, depending on the mass of the nucleus. Based on a binding energy curve, similar to the one titled "Fission and fusion can yield energy" found on the HyperPhysics page hosted by Georgia State University, what element appears to have the most stable nucleus? How do you know from the graph?

4. Fusion reactions join small nuclei together to create larger nuclei. Based on that graph, would fusion reactions of nuclei that result in nuclei that are less massive than iron consume or release net energy?

5. Based on that graph, would fusion reactions that result in nuclei that are more massive than iron consume or release net energy?

6. For a given mass of fuel, which releases more energy — fusion of very light elements to form a stable nuclei, or fission of a very heavy element to form stable nuclei? Use the graph.

PHYSICAL SCIENCES

Discussion questions:

1. How does a star form?

2. How does a star live?

3. How does a star die?

Extension prompts:

4. What is a Hertzsprung-Russell diagram?

ENGINEERING AND EXPERIMENTAL DESIGN

Discussion questions:

1. How long did it take light and gravitational waves to travel from the neutron star collision to earth? How long ago did the collision actually happen?

2. The New Horizons probe that flew by Pluto in 2015 is traveling away from our solar system at approximately 52,000 kilometers per hour. What fraction of light speed is that? If New Horizons were traveling toward NGC 4993 and kept that same velocity, how long would it take to reach from Earth whatever is left of the neutron star collision?

Extension prompts:

3. What sorts of things could we monitor or learn from satellites with similar sensors that are pointed inward toward Earth instead of outward toward space?

4. How might the gravitational wave detectors be improved?

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Activity Guide for Teachers: The Pressure to Be a Star

Purpose: To understand the life cycle of stars and how stars produce various elements.

Procedural overview: Students can use basic algebra, physics and chemistry principles to estimate the conditions involved in stars and element formation.

Approximate class time: 30-50 minutes.

Materials:

- Activity guide for students: The Pressure to Be a Star
- Calculators with scientific notation

Notes to the teacher:

This activity makes extensive use of these basic concepts, so if necessary, please review them in advance with your students:

- Scientific notation
- Newton's law of gravity
- Ideal gas law

In order to keep the math and physics simple, this activity involves some crude approximations and plenty of hand waving. For more detailed calculations that arrive at similar final results, please see for example:

M. Schwarzschild. *Structure and Evolution of the Stars*. Dover, 1958.

R. Kippenhahn and A. Weigert. *Stellar Structure and Evolution*. Springer-Verlag, 1990.

S. L. Shapiro and S. A. Teukolsky. *Black Holes, White Dwarfs, and Neutron Stars*. Wiley, 1983.

Questions for students, with suggested answers:

Defined constants needed in the calculations:

- Speed of light = c = 3.00×10^8 m/sec
- Gravitational constant = G = 6.67×10^{-11} m^3/(kg•s^2)

1. Our sun is a fairly typical star, so we will do most of our calculations using it. The sun's average radius is $r = 6.96 \times 10^8$ m. Assuming that the sun is perfectly spherical (it is actually slightly oblate or squished), what is its volume?

$V_{sun} = (4/3)\ \pi\ r^3 =$ *1.41×10^{27} m^3*

2. For comparison, Earth's average radius is approximately 6.37×10^6 m. What is Earth's volume, and how many Earths would fit inside the sun?

$V_{Earth} =$ *1.08×10^{21} m^3, so 1.3 million Earths would fit inside the sun*

3. The sun's mass is $M = 1.99 \times 10^{30}$ kg. What is the sun's average mass density, and how does that compare to the density of water (1000 kg/m^3)?

$\rho_{avg} = M/V =$ *1410 kg/m^3, so 1.41 times the density of water*

4. Since the sun is neither contracting nor expanding, the gravitational force pulling matter inward toward the center of the sun must be equal to the outward force of gas pressure generated by the heat of fusion reactions, a condition known as hydrostatic balance. Detailed equations for hydrostatic balance may be found using calculus, but a simple estimate can be made with algebra. From Newton's law of gravity, the gravitational force pulling inward on matter of density ρ_{avg} near the outer edge of the sun would be $G\rho_{avg}M/r^2$. If the pressure at the center of the sun is P_c, the average pressure gradient between the center of the sun and its edge is P_c/r. Setting those two forces equal would give $P_c/r = G\rho_{avg}M/r^2$, or $P_c = G\rho_{avg}M/r$. In reality, the pressure is much more concentrated in the center of the sun than that linear estimate suggests — roughly 100 times as concentrated — so a decent approximation is $P_c = 100\ G\rho_{avg}\ M/r$.

Using this approximation, what is the pressure at the center of the sun, and how does it compare with the pressure of Earth's atmosphere at sea level (1.01×10^5 Pa)? Solve the equation for a numerical answer, and also solve the equation using the appropriate units (1 Pa = kg/(m•s^2)).

$P_c = 100\ G\rho_{avg}M/r =$ *2.69×10^{16} Pa, so 2.66×10^{11} times Earth's atmospheric pressure*

5. Our assumption was that the pressure is concentrated 100-fold in the center compared with a simple linear estimate. That will compress the density to 100 times the average density. Calculate the density in the center of the sun:

$\rho_c = 100\ \rho_{avg} =$ *1.41×10^5 kg/m^3*

6. Using the ideal gas law with a gas constant for monatomic hydrogen gas, R = 8315 J/(kg•K), the central pressure would be related to the central density and central temperature as $P_c = R\ \rho_c\ T_c$. But hydrogen in the sun is ionized, so its protons and its electrons each contribute that much pressure, and the total pressure is doubled, $P_c = 2\ R\ \rho_c\ T_c$.

What is the temperature at the center of the sun?

$T_c = P_c/(2\ R\ \rho_c) =$ *1.15×10^7 K*

(Note: The actual value is 1.5×10^7 K, so we did well considering how crude our approximations were.)

7. Normal room temperature is around 295 Kelvin (K). How many times hotter than room temperature is the center of the sun?

Roughly 40,000–50,000 times hotter.

8. Based on the temperature thresholds at which these fusion reactions become significant, which of these reactions are most dominant in the sun?

$T_c > 8 \times 10^6$ K : proton-proton fusion to produce ^4He from protons

$T_c > 1.8 \times 10^7$ K : carbon-catalyzed (CNO) fusion to produce ^4He from protons

$T_c > 1 \times 10^8$ K : helium burning $^4He + {}^4He \rightarrow {}^8Be$ and $^8Be + {}^4He \rightarrow {}^{12}C + \gamma$

$T_c > 1 \times 10^8$ to 1×10^9 K: $^{12}C + {}^4He \rightarrow {}^{16}O + \gamma$ and $^{12}C + {}^{12}C \rightarrow {}^{23}Na + {}^1H$

Proton-proton fusion is dominant. There is a little carbon-catalyzed fusion.

9. Fusing protons together forms helium-4 nuclei, also called α particles. The mass of one proton is $m_p = 1.6726 \times 10^{-27}$ kg. The mass of one α-particle is $m_\alpha = 6.6442 \times 10^{-27}$ kg. The total mass of four protons is larger than the mass of the helium-4 nucleus that the protons produced through fusion, so the excess mass is converted into energy. How much energy is produced by forming one α-particle?

$E = (4m_p - m_\alpha)c^2 = 4.16 \times 10^{-12}\ J$

10. The sun produces approximately 3.84×10^{26} W (J/sec) of energy. How many α-particles does it produce per second?

9.24×10^{37} α-particles per second

11. How much solar mass gets converted from hydrogen to helium per second?

6.18×10^{11} kg/sec (4 m_p x number of α-particles produced per second)

12. If a neutron has a mass $m_n = 1.6749 \times 10^{-27}$ kg and an average effective radius of 9.41×10^{-16} m, what is its density?

$\rho_{neutron} = 4.80 \times 10^{17}\ kg/m^3$ *(Solve for $V_{neutron}$, then $\rho_{neutron} = m_n/V_{neutron}$)*

13. If all the matter in the sun were compressed to form a neutron star with the same density as for the neutron you just calculated, how much more dense would that be than the sun's current average density?

3.40×10^{14} times more dense ($\rho_{avg} / \rho_{neutron}$)

14. If all the matter in the sun were compressed to form such a neutron star, what would its radius be?

9970 m = about 10 km ($V_{neutron\ star} = (4/3)\ \pi\ r_{neutron\ star}^3 = M_{sun}/\rho_{neutron}$, solve for $r_{neutron\ star}$)

Typical neutron stars are only somewhat more massive than the sun, so that is actually a good estimate of the radius of real neutron stars.

15. A mass M must be compressed to a Schwarzschild radius of R_S to become a black hole. R_S is also the point at which light cannot escape. The escape velocity for an object from a given radius is that such that

the object's positive kinetic energy is sufficient enough to cancel out the object's negative gravitational potential energy, $mv^2/2 - GMm/R = 0$, or $R = 2GM/v^2$. If light cannot escape, v=c, one finds the Schwarzschild radius $R_S = 2GM/c^2$. If the sun were compressed to form a black hole, what would its Schwarzschild radius be?

$R_S = 2GM/c^2 =$ *2950 m = about 3 km*

16. Out of all of these facts and numbers, what surprises you the most?

Student answers will vary.

17. What other relevant characteristics or effects can you calculate using your knowledge of math and science?

Student answers will vary.

SN EDUCATOR GUIDE

November 11, 2017

Neutron Star Crash Seen for First Time

Activity Guide for Students: The Pressure to Be a Star

Purpose: To understand the life cycle of stars and how stars produce various elements.

Procedural overview: Use basic algebra, physics and chemistry principles to estimate the conditions involved in stars and element formation.

Defined constants needed in the calculations:

- Speed of light = c = 3.00×10^{8} m/sec
- Gravitational constant = G = 6.67×10^{-11} $m^3/(kg•s^2)$

1. Our sun is a fairly typical star, so we will do most of our calculations using it. The sun's average radius is r = 6.96×10^{8} m. Assuming that the sun is perfectly spherical (it is actually slightly oblate or squished), what is its volume?

2. For comparison, Earth's average radius is approximately 6.37×10^{6} m. What is Earth's volume, and how many Earths would fit inside the sun?

3. The sun's mass is M = 1.99×10^{30} kg. What is the sun's average mass density, and how does that compare to the density of water (1000 kg/m^3)?

4. Since the sun is neither contracting nor expanding, the gravitational force pulling matter inward toward the center of the sun must be equal to the outward force of gas pressure generated by the heat of fusion reactions, a condition known as hydrostatic balance. Detailed equations for hydrostatic balance may be found using calculus, but a simple estimate can be made with algebra. From Newton's law of gravity, the gravitational force pulling inward on matter of density ρ_{avg} near the outer edge of the sun would be $G\rho_{avg}M/r^2$. If the pressure at the center of the sun is P_c, the average pressure gradient between

the center of the sun and its edge is P_c/r. Setting those two forces equal would give $P_c/r = G\rho_{avg}M/r^2$, or $P_c = G\rho_{avg}M/r$. In reality, the pressure is much more concentrated in the center of the sun than that linear estimate suggests — roughly 100 times as concentrated — so a decent approximation is $P_c = 100\ G\rho_{avg}\ M/r$.

Using this approximation, what is the pressure at the center of the sun, and how does it compare with the pressure of Earth's atmosphere at sea level (1.01×10^5 Pa)? Solve the equation for a numerical answer, and also solve the equation using the appropriate units (1 Pa = kg/(m•s^2)).

5. Our assumption was that the pressure is concentrated 100-fold in the center compared with a simple linear estimate. That will compress the density to 100 times the average density. Calculate the density in the center of the sun:

6. Using the ideal gas law with a gas constant for monatomic hydrogen gas, R = 8315 J/(kg•K), the central pressure would be related to the central density and central temperature as $P_c = R\ \rho_c\ T_c$. But hydrogen in the sun is ionized, so its protons and its electrons each contribute that much pressure, and the total pressure is doubled, $P_c = 2\ R\ \rho_c\ T_c$.

What is the temperature at the center of the sun?

7. Normal room temperature is around 295 Kelvin (K). How many times hotter than room temperature is the center of the sun?

8. Based on the temperature thresholds at which these fusion reactions become significant, which of these reactions are most dominant in the sun?

$T_c > 8 \times 10^6$ K : proton-proton fusion to produce ^{4}He from protons

$T_c > 1.8 \times 10^7$ K : carbon-catalyzed (CNO) fusion to produce ^{4}He from protons

$T_c > 1 \times 10^8$ K : helium burning $^4He + ^4He \rightarrow ^8Be$ and $^8Be + ^4He \rightarrow ^{12}C + \gamma$

$T_c > 1 \times 10^8$ to 1×10^9 K: $^{12}C + ^4He \rightarrow ^{16}O + \gamma$ and $^{12}C + ^{12}C \rightarrow ^{23}Na + ^1H$

9. Fusing protons together forms helium-4 nuclei, also called α particles. The mass of one proton is $m_p = 1.6726 \times 10^{-27}$ kg. The mass of one α-particle is $m_\alpha = 6.6442 \times 10^{-27}$ kg. The total mass of four protons is larger than the mass of the helium-4 nucleus that the protons produced through fusion, so the excess mass is converted into energy. How much energy is produced by forming one α-particle?

10. The sun produces approximately 3.84×10^{26} W (J/sec) of energy. How many α-particles does it produce per second?

11. How much solar mass gets converted from hydrogen to helium per second?

12. If a neutron has a mass $m_n = 1.6749 \times 10^{-27}$ kg and an average effective radius of 9.41×10^{-16} m, what is its density?

13. If all the matter in the sun were compressed to form a neutron star with the same density as for the neutron you just calculated, how much more dense would that be than the sun's current average density?

14. If all the matter in the sun were compressed to form such a neutron star, what would its radius be?

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