Process of Science: Observations versus Model-Based Statements about the Sun

Learning Goal:
To understand the interplay between observations and theoretical modeling in our current scientific understanding of the Sun.

Introduction. The source of the Sun’s energy was a mystery for thousands of years, but today we think we have a very good understanding of how the Sun works and why it shines so steadily. This activity will help you appreciate how we have developed this understanding of the Sun through a combination of observations and theoretical modeling.

Part A
To understand the interplay of observations and models you must first be able to distinguish between things that we observe and things that we infer from models. Consider the following statements about the Sun. Classify each statement as an observation or as an inference based on the current, accepted model for the Sun.

Hint 1. How do we learn about the center of the Sun?
Our current understanding of nuclear fusion in the Sun’s core is based primarily on _________.
ANSWER:
- observing Doppler shifts from gas in the Sun’s visible photosphere
- measurements made by space probes that have sampled the gas in the Sun’s core
- applying the laws of physics to calculate what must be occurring inside the Sun

Hint 2. What are the various “layers” of the Sun?
Which of the following lists the Sun’s layers in the correct order (starting from the Sun’s center and going outward)?
ANSWER:
- core, convection zone, photosphere, chromosphere, corona, radiation zone
- core, radiation zone, convection zone, photosphere, chromosphere, corona
- core, radiation zone, convection zone, chromosphere, corona, photosphere

Hint 3. Which layers of the Sun can be seen with a telescope?
Which of the following statements accurately describes how we can best study different layers of the Sun with telescopes either on the ground or in space?
ANSWER:
- We observe the photosphere with visible-light telescopes, the radiation zone with ultraviolet-light telescopes, and the core with X-ray telescopes.
- We observe the corona with visible-light telescopes, the chromosphere with ultraviolet-light telescopes, and the photosphere with X-ray telescopes.
- We observe the photosphere with visible-light telescopes, the chromosphere with ultraviolet-light telescopes, and the corona with X-ray telescopes.

Hint 4. Definition of a neutrino
A neutrino is a lightweight (almost massless) particle that is a by-product of nuclear reactions and radioactive decay. Neutrinos have the unusual property that they do not interact with light, and therefore they do not respond to the electromagnetic forces that affect protons and electrons. Neutrinos can therefore stream outward from the center of the Sun nearly uninterrupted by collisions. We can detect them (by looking for their very rare collisions with other particles) on Earth with the help of gigantic underground detectors such as South Dakota’s Homestake Mine and the Sudbury Neutrino Observatory in Canada.
ANSWER:
Today, most scientists would say that all of the statements from Part A are "true," even though some of them are inferences from models. Scientists have this confidence because current solar models are so successful in predicting observable characteristics of the Sun. The following set of questions should help ensure that you understand the interplay of observation and modeling.

Part B

One statement about the Sun from Part A is "The corona is hotter than the photosphere." Which of the following statements provides observational evidence for this claim?

**Hint 1. What are the various "layers" of the Sun?**

Which of the following lists the Sun's layers in the correct order (starting from the Sun's center and going outward)?

**ANSWER:**
- core, radiation zone, convection zone, chromosphere, corona, photosphere
- core, radiation zone, convection zone, photosphere, chromosphere, corona
- core, convection zone, photosphere, chromosphere, corona, radiation zone

**Hint 2. Which layers of the Sun can be seen with a telescope?**

Which of the following statements accurately describes how we can best study different layers of the Sun with telescopes either on the ground or in space?

**ANSWER:**
- We observe the photosphere with visible-light telescopes, the chromosphere with ultraviolet-light telescopes, and the corona with X-ray telescopes.
- We observe the photosphere with visible-light telescopes, the radiation zone with ultraviolet-light telescopes, and the core with X-ray telescopes.
- We observe the corona with visible-light telescopes, the chromosphere with ultraviolet-light telescopes, and the photosphere with X-ray telescopes.

**ANSWER:**
- The corona primarily emits X rays while the photosphere primarily emits visible light.
- The corona emits much less total light than the photosphere.
- The corona has a much lower gas density than the photosphere.
- The corona is higher in the Sun’s atmosphere than the photosphere.
In general, higher temperature gas emits higher energy light. The fact that the corona emits primarily in X rays therefore indicates that it consists of higher temperature gas than visible-light-emitting photosphere.

Part C

Now consider the statements in Part A that are inferred from models. A solar model is used to calculate interior conditions based on certain "known" characteristics of the Sun, such as the Sun’s total mass. How do we know the Sun's mass?

**Hint 1. Statement of Newton's version of Kepler's third law**

Newton’s version of Kepler's third law relates the orbital periods, distances, and masses of any pair of orbiting objects. If one object is much more massive than the other, as is the case with the Sun and a planet or a planet and a moon, the law becomes

\[
p^2 = \frac{4\pi^2}{GM} a^3
\]

where \( G \) is the gravitational constant, \( M \) is the mass of the massive object, and \( p \) and \( a \) are the orbital period and distance, respectively, of the smaller object orbiting around the massive object.

**ANSWER:**

- We can calculate it by using the law of conservation of energy with the measured amount of light that the Sun emits.
- We first measure the Sun's size and density, then use these measurements to calculate the Sun's mass.
- We infer the mass from a model of the Sun.
- We can calculate it by applying Newton's version of Kepler's third law with Earth's orbital period (1 year) and Earth's average distance from the Sun (1 AU).

Recall that Newton’s version of Kepler’s third law allows us to calculate the mass of any object if we know the orbital period and distance of a much smaller object that orbits it. This means we can use not only Earth’s period and distance to calculate the Sun’s mass but the period and distance of any planet or even of a spaceship that we put into solar orbit.

Part D

A solar model is used to calculate the expected temperature and density at all depths within the Sun. These results are then used to calculate the expected fusion rate within the Sun. We have confidence that the model is correct because it agrees with the observed characteristics of the Sun. Which of the following observations can be used to check that we really do know the Sun's internal fusion rate?

Select all that apply.

**Hint 1. Definition of a neutrino**

A neutrino is a lightweight (almost massless) particle that is a by-product of nuclear reactions and radioactive decay. Neutrinos have the unusual property that they do not interact with light, and therefore they do not respond to the electromagnetic forces that affect protons and electrons. Neutrinos can therefore stream outward from the center of the Sun nearly uninterrupted by collisions. We can detect them (by looking for their very rare collisions with other particles) on Earth with the help of gigantic underground detectors such as South Dakota’s Homestake Mine and the Sudbury Neutrino Observatory in Canada.

**ANSWER:**

- Measurements of the Sun's total energy output into space
- Observations of the total X-ray emission from the Sun's corona
- Measurements of the varying number of sunspots on the Sun over time
- Observations of neutrinos coming from the Sun
- Measurement of the Sun's mass

The Sun shines with energy generated by fusion, so the total rate at which the Sun emits energy into space must be equal to the rate at which it generates energy by fusion in the core. Neutrinos are a product of fusion reactions, so they provide direct evidence concerning fusion in the core.

**Concept Quiz**
In the late 1800s, Kelvin and Helmholtz suggested that the Sun stayed hot due to gravitational contraction. What was the major drawback to this idea?

**Hint 1.**
Study Section 14.1 of *The Cosmic Perspective*.

**ANSWER:**
- It predicted that the Sun would shrink noticeably as we watched it, but the Sun appears to be stable in size.
- It predicted that Earth would also shrink in size with time, which would make it impossible to have stable geology on our planet.
- It is physically impossible to generate heat simply by making a star shrink in size.
- It predicted that the Sun could shine for about 25 million years, but geologists had already found that Earth is much older than this.

This was indeed a major drawback to the idea. Clearly, Earth could not have had life before the Sun was shining.

**Part B**
When is/was gravitational contraction an important energy generation mechanism for the Sun?

**Hint 1.**
Study Section 14.1 of *The Cosmic Perspective*.

**ANSWER:**
- It was important when the Sun was forming from a shrinking interstellar cloud of gas.
- It is important during periods when the Sun is going from solar maximum to solar minimum.
- It has played a role throughout the Sun's history, but it was most important right after nuclear fusion began in the Sun's core.
- It is the primary energy generation mechanism in the Sun today.

The shrinkage of the cloud meant that particles were losing gravitational potential energy, which could be converted into thermal energy.

**Part C**
What do we mean when we say that the Sun is in gravitational equilibrium?

**Hint 1.**
Study Section 14.1 of *The Cosmic Perspective*.

**ANSWER:**
- The Sun maintains a steady temperature.
- The Sun always has the same amount of mass, creating the same gravitational force.
- The hydrogen gas in the Sun is balanced so that it never rises upward or falls downward.
- There is a balance within the Sun between the outward push of pressure and the inward pull of gravity.

This balance is very important to understanding the Sun and all other stars.

**Part D**
Which of the following is the best answer to the question, "Why does the Sun shine?"

**Hint 1.**
Study Section 14.1 of *The Cosmic Perspective*.
This statement does indeed summarize our current understanding of why the Sun shines.

**Part E**

How does the Sun's mass compare to Earth's mass?

**Hint 1.**

Study Section 14.1 of *The Cosmic Perspective.*

**ANSWER:**

- Both have approximately the same mass.
- The Sun's mass is about 300,000 times the mass of the Earth.
- The Sun's mass is about 300 times the mass of the Earth.
- The Sun's mass is about 30 times the mass of the Earth.

Indeed, the Sun's mass is more than 1,000 times that of all the planets combined.

**Part F**

Which of the following best describes why the Sun emits most of its energy in the form of visible light?

**Hint 1.**

Review the laws of thermal radiation and study Section 14.1 of *The Cosmic Perspective.*

**ANSWER:**

- The visible light comes from energy level transitions as electrons in the Sun's hydrogen atoms jump between level 1 and level 2.
- Nuclear fusion in the Sun's core produces visible light photons.
- Like all objects, the Sun emits thermal radiation with a spectrum that depends on its temperature, and the Sun's surface temperature is just right for emitting mostly visible light.
- The Sun's gas is on fire like flames from wood or coal, and these flames emit visible light.

The Sun's 5,800 K surface temperature means it emits most of its radiation as visible light. (If you are unsure why, review the laws of thermal radiation in Chapter 5 of *The Cosmic Perspective.*)

**Part G**

The Sun's surface seethes and churns with a bubbling pattern. Why?

**Hint 1.**

Study Section 14.1 of *The Cosmic Perspective.*
You can see this idea by studying the figure of the Sun's structure in your textbook, in which you'll see that the convection zone lies just beneath the photosphere.

Part H
Which of the following correctly compares the Sun's energy generation process to the energy generation process in human-built nuclear power plants?

Hint 1.
Study Section 14.2 of The Cosmic Perspective.

ANSWER:
- The Sun generates energy by fusing small nuclei into larger ones, while our power plants generate energy by the fission (splitting) of large nuclei.
- The Sun generates energy through fission while nuclear power plants generate energy through fusion.
- Both processes involve nuclear fusion, but the Sun fuses hydrogen while nuclear power plants fuse uranium.
- The Sun generates energy through nuclear reactions while nuclear power plants generate energy through chemical reactions.

That is, the Sun produces energy through nuclear fusion while our nuclear power plants produce energy through nuclear fission.

Part I
Every second, the Sun converts about 600 million tons of hydrogen into 596 million tons of helium. The remaining 4 million tons of mass is _________.

Hint 1.
Study Section 14.2 of The Cosmic Perspective.

ANSWER:
- Converted to an amount of energy equal to 4 million tons times the speed of light squared
- Ejected into space in a solar wind
- Reabsorbed as molecular hydrogen
- Ejected into space by solar flares

Einstein's famous equation, $E = mc^2$, explains what happens to the "missing" four million tons of mass.

Part J
Which of the following best explains why nuclear fusion requires bringing nuclei extremely close together?

Hint 1.
Study Section 14.2 of The Cosmic Perspective.

ANSWER:
- The churning is an illusion created by varying radiation, as the gas on the Sun's surface is actually quite still.
- We are seeing hot gas rising and cool gas falling due to the convection that occurs beneath the surface.
- The churning gas is being stirred up by the strong solar wind.
- The Sun's surface is boiling.
The strong force acts only across extremely short distances - such as the distance across a nucleus - and so the particles must be brought very close together before they can fuse.

Part K
If the Sun's core suddenly shrunk a little bit, what would happen in the Sun?

**Hint 1.**
Study Section 14.2 of *The Cosmic Perspective."

**ANSWER:**

- The density of the core would decrease, causing the core to cool off and expand.
- The core would cool off and continue to shrink as its density increased.
- The core would heat up, fusion rates would increase, the core would re-expand.
- The core would heat up, causing it to radiate so much energy that it would shrink even more.

This is why the "solar thermostat" is so effective at maintaining a steady temperature.

Part L
Why does the Sun emit neutrinos?

**Hint 1.**
Study Section 14.2 of *The Cosmic Perspective."

**ANSWER:**

- Fusion in the Sun's core creates neutrinos.
- The Sun was born with a supply of neutrinos that it gradually emits into space.
- Solar flares create neutrinos with magnetic fields.
- Convection releases neutrinos, which random walk through the radiation zone.
- The Sun does not emit neutrinos.

Neutrinos are a byproduct of a fusion reaction.

Part M
If the Sun suddenly stopped emitting neutrinos, what might we infer (after checking that our neutrino detectors were still operational)?

**Hint 1.**
Study Section 14.2 of *The Cosmic Perspective."

**ANSWER:**

- The density of the core would decrease, causing the core to cool off and expand.
- The core would cool off and continue to shrink as its density increased.
- The core would heat up, fusion rates would increase, the core would re-expand.
- The core would heat up, causing it to radiate so much energy that it would shrink even more.

Fusion in the Sun's core creates neutrinos.

The Sun was born with a supply of neutrinos that it gradually emits into space.

Solar flares create neutrinos with magnetic fields.

Convection releases neutrinos, which random walk through the radiation zone.

The Sun does not emit neutrinos.
Neutrinos are produced by fusion reactions and, because they interact so rarely with matter, they travel directly to Earth at nearly the speed of light, reaching Earth about 8 minutes after they are produced. So if we stopped receiving neutrinos, we would know that fusion reactions had stopped.

**Part N**

Which of the following best explains why the Sun's luminosity gradually rises over billions of years?

**Hint 1.**
Study Section 14.2 of The Cosmic Perspective.

**ANSWER:**

- The particle number decreases because each fusion reaction converts 4 hydrogen nuclei into just 1 helium nucleus.
- The planets need more and more energy to maintain any life on them as time goes on, and therefore the Sun must get hotter.
- Fusion gradually decreases the number of independent particles in the core, allowing gravity to compress and heat the core, which in turn increases the fusion rate and the Sun's luminosity.
- Nuclear reactions in the Sun become more efficient with time, so that each fusion reaction releases more energy when the Sun is old than when it is young; this in turn raises the Sun's luminosity.
- The Sun's core gradually expands with time, and this expansion means there is more room for energy to be generated and hence increases the Sun's luminosity.

In other words, sunspots are hot enough to emit visible light; they are just cooler (and hence less bright) than surrounding plasma.

**Part P**

The star Alpha Centauri A is the same type of star as the Sun, but its luminosity is about 1.6 times that of the Sun. What can we conclude?

**Hint 1.**
Study Section 14.2 of The Cosmic Perspective, and think about how energy balance works in stars.

**ANSWER:**

- Fission reactions in the Sun have ceased.
- Fusion reactions in the Sun have ceased.
- Fusion reactions in the Sun ceased a few hundred thousand years ago.
- The Sun has exhausted its supply of neutrinos.
Energy balance requires that the luminosity emerging from the surface of the star is equal to the energy generation rate in the core, so a higher luminosity means a higher energy generation rate.

Part Q

How can we best observe the Sun's chromosphere and corona?

**Hint 1.**
Study Section 14.3 of *The Cosmic Perspective.*

**ANSWER:**

- The chromosphere and corona are both best studied with visible light.
- The chromosphere and corona are both best studied with radio telescopes.
- The chromosphere is best observed with infrared telescopes and the corona is best observed with ultraviolet telescopes.
- The chromosphere is best observed with ultraviolet telescopes and the corona is best observed with X-ray telescopes.

The chromosphere is hot enough to emit mostly ultraviolet light and the corona to emit mostly X rays.

Part R

The intricate patterns visible in an X-ray image of the Sun generally show ________.

**Hint 1.**
Study Section 14.3 of *The Cosmic Perspective.*

**ANSWER:**

- helioseismological fluctuations
- a bubbling pattern on the photosphere
- structure within sunspots
- extremely hot plasma flowing along magnetic field lines

This very hot gas produces X rays and hence is what we see in X-ray images.

Part S

How can we measure the strength of magnetic fields on the Sun?

**Hint 1.**
Study Section 14.3 of *The Cosmic Perspective.*

**ANSWER:**

- Alpha Centauri A has a much higher surface temperature than the Sun.
- Alpha Centauri A must have a vastly different interior structure than the Sun.
- Alpha Centauri A is much farther from Earth than the Sun.
- Alpha Centauri A fuses hydrogen into helium in its core at a higher rate than our Sun.
Magnetic fields can cause some spectral lines to split, so we can measure the Sun's magnetic field strength by measuring the splitting of spectral lines. (This splitting of spectral lines is often called the Zeeman effect.)

**Part T**

Satellites in low-Earth orbits are more likely to crash to Earth when the sunspot cycle is near solar maximum because ________.

**Hint 1.**

Study Section 14.3 of *The Cosmic Perspective*.

**ANSWER:**

- The increase in solar X rays and high energy particles from the Sun that occur during solar maximum causes Earth's upper atmosphere to expand.

**Part U**

Which of the following choices is not a way by which we can study the inside of the Sun?

**Hint 1.**

Study Section 14.2 of *The Cosmic Perspective*.

**ANSWER:**

- We can send a space probe into the Sun's photosphere.
- We can make a computer model of the Sun's interior that allow us to predict the observable properties of the Sun.
- We can probe the interior of the Sun by studying the vibrations in its photosphere.

**Part V**

A computer accessory salesman attempts to convince you to purchase a "solar neutrino" shield for your new computer. (It's even "on sale" !) Why do you turn down this excellent offer?

**Hint 1.**

Study Sections 14.2 and 14.3 of *The Cosmic Perspective*.

**ANSWER:**

- By observing the sizes of sunspots: Bigger sunspots mean a stronger field.
- By looking for the splitting of spectral lines in the Sun's spectrum.
- By observing auroras here on Earth.
In fact, neutrinos rarely interact with matter of any kind, so it would be pointless to have a neutrino shield, even if such a shield were possible (which it's not, since the neutrinos won't interact with the shield either).

**Problem 14.29**

Choose the best answer.

**Part A**

Which of these groups of particles has the greatest mass?

ANSWER:

- a helium nucleus with two protons and two neutrons
- four electrons
- four individual protons

**Problem 14.32**

Choose the best answer.

**Part A**

Scientists estimate the central temperature of the Sun using

ANSWER:

- probes that measure changes in Earth's atmosphere.
- mathematical models of the Sun.
- laboratories that create miniature versions of the Sun.

**Problem 14.36**

Choose the best answer.

**Part A**

How does the number of neutrinos passing through your body at night compare with the number passing through your body during the day?

ANSWER:

- about the same
- much smaller
- much larger
Part A

Estimate how much mass the Sun loses through fusion reactions during its 10-billion-year life. You can simplify the problem by assuming the Sun’s energy output remains constant.

**ANSWER:**

\[ m_{\text{lost}} = 1.33 \times 10^{27} \text{ kg} \]

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Part B

Compare the amount of mass lost with Earth’s mass.

**ANSWER:**

\[ \frac{m_{\text{lost}}}{m_{\text{Earth}}} = 223 \]

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**Reading Quiz**

Part A

According to modern science, approximately how old is the Sun?

**Hint 1.**

Study Section 14.1 of *The Cosmic Perspective.*

**ANSWER:**

- 10,000 years
- 400 million years.
- 4 1/2 billion years
- 25 million years

The Sun is the same age as the rest of our solar system, which from earlier chapters is 4 Â½ billion years.

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Part B

The Sun will exhaust its nuclear fuel in about ______.

**Hint 1.**

Study Section 14.1 of *The Cosmic Perspective.*

**ANSWER:**

- 5 million years
- 5000 AD
- 50 billion years
- 5 billion years

The Sun’s total life time is about 10 billion years, and the Sun is only about halfway through this lifetime at present.
Part C
Which of the following correctly describes how the process of gravitational contraction can make a star hot?

**Hint 1.**
Study Section 14.1 of *The Cosmic Perspective*.

**ANSWER:**
- When a star contracts in size, gravitational potential energy is converted to thermal energy.
- Gravitational contraction involves the generation of heat by chemical reactions, much like the burning of coal.
- Heat is generated when gravity contracts, because gravity is an inverse square law force.
- Gravitational contraction involves nuclear fusion, which generates a lot of heat.

This process is called gravitational contraction because gravity is what makes the star contract.

Part D
What two physical processes balance each other to create the condition known as gravitational equilibrium in stars?

**Hint 1.**
Study Section 14.1 of *The Cosmic Perspective*.

**ANSWER:**
- the strong force and the electromagnetic force
- the strong force and the weak force
- gravitational force and surface tension
- gravitational force and outward pressure

This dynamic is important for understanding stellar structure and stellar evolution.

Part E
The source of energy that keeps the Sun shining today is ________.

**Hint 1.**
Study Section 14.1 of *The Cosmic Perspective*.

**ANSWER:**
- chemical reactions
- gravitational contraction
- nuclear fission
- nuclear fusion

The Sun shines by fusing hydrogen into helium, a process in which a small amount of the mass is converted into energy.
Part F
When we say that the Sun is a ball of plasma, we mean that ________.  

**Hint 1.**
Study Section 14.1 of *The Cosmic Perspective.*

**ANSWER:**
- the Sun is made of material that acts like a liquid acts on Earth
- the Sun is roughly the same color as blood
- the Sun consists of gas in which many or most of the atoms are ionized (missing electrons)
- the Sun is made of atoms and molecules

A plasma is an ionized gas, and the Sun is so hot that most of its gas is ionized.

Part G
What is the Sun made of (by mass)?

**Hint 1.**
Study Section 14.1 of *The Cosmic Perspective.*

**ANSWER:**
- 70% hydrogen, 28% helium, 2% other elements
- 50% hydrogen, 25% helium, 25% other elements
- 100% hydrogen and helium
- 90% dark matter, 10% ordinary matter

This is also the approximate overall chemical composition of the Milky Way Galaxy and the rest of the universe today.

Part H
From center outward, which of the following lists the "layers" of the Sun in the correct order?

**Hint 1.**
Study Section 14.1 of *The Cosmic Perspective.*

**ANSWER:**
- Core, radiation zone, convection zone, photosphere, chromosphere, corona
- Core, convection zone, radiation zone, corona, chromosphere, photosphere
- Core, corona, radiation zone, convection zone, photosphere, chromosphere
- Core, radiation zone, convection zone, corona, chromosphere, photosphere

Be sure to study the figure in your text to make sure you understand the structures of these layers.

Part I
What are the appropriate units for the Sun's luminosity?

**Hint 1.**
Mandatory Assignment 2 - Testing material from Chapter 14

Study Section 14.1 of *The Cosmic Perspective*.

**ANSWER:**

- ✗ watts
- ✗ kilograms
- ✗ newtons
- ✗ joules

Luminosity measures energy output per second, which corresponds to units of watts.

**Part J**

The Sun's surface, as we see it with our eyes, is called the ________.

**Hint 1.**

Study Section 14.1 of *The Cosmic Perspective*.

**ANSWER:**

- ✓ corona
- ✗ photosphere
- ✗ chromosphere
- ✗ core

The prefix *photo* means "light" - usually taken to imply visible light - so the photosphere is the visible surface (sphere) of the Sun.

**Part K**

The Sun's average surface (photosphere) temperature is about _____.

**Hint 1.**

Study Section 14.1 of *The Cosmic Perspective*.

**ANSWER:**

- ✗ 1,000 K
- ✗ 5,800 K
- ✗ 1,000,000 K
- ✗ 37,000 K

Note that this is a temperature at which most thermal radiation is in the visible part of the spectrum - which is why the Sun radiates most of its energy as visible light.

**Part L**

What is the *solar wind*?

**Hint 1.**

Study Section 14.1 of *The Cosmic Perspective*.

**ANSWER:**
The solar wind blows outward in all directions and has important effects on the planets, especially through interactions with planetary magnetospheres.

Part M
The fundamental nuclear reaction occurring in the core of the Sun is __________.

**Hint 1.**
Study Section 14.2 of *The Cosmic Perspective.*

**ANSWER:**

- radioactive decay
- nuclear fusion of hydrogen into helium
- nuclear fission
- nuclear fusion of helium to carbon

Each complete reaction converts four hydrogen nuclei (protons) into 1 helium nucleus, although the reaction proceeds through several smaller steps.

Part N
The *proton-proton chain* is __________.

**Hint 1.**
Study Section 14.2 of *The Cosmic Perspective.*

**ANSWER:**

- another name for the force that holds protons together in atomic nuclei
- the specific set of nuclear reactions through which the Sun fuses hydrogen into helium
- an alternative way of generating energy that is different from the fusion of hydrogen into helium
- the linkage of numerous protons into long chains

That is, the proton-proton chain is just one pathway by which hydrogen can be fused into helium.

Part O
The overall result of the proton-proton chain is:

**Hint 1.**
Study Section 14.2 of *The Cosmic Perspective.*

**ANSWER:**

- a stream of charged particles flowing outward from the surface of the Sun
- the wind that causes huge arcs of gas to rise above the Sun's surface
- the strong wind that blows sunspots around on the surface of the Sun
- the uppermost layer of the Sun, lying just above the corona
The helium nucleus has a slightly lower mass than the four hydrogen nuclei combined, so the difference is converted to energy in accord with $E = mc^2$.

**Part P**

To estimate the central temperature of the Sun, scientists ________.

*Hint 1.*

Study Section 14.2 of *The Cosmic Perspective.*

**ANSWER:**

- send probes to measure the temperature
- monitor changes in Earth's atmosphere
- use hot gas to create a small Sun in a laboratory
- use computer models to predict interior conditions

Computer models are used to model internal core temperatures in the Sun and to make testable predictions about the Sun's observable properties.

**Part Q**

Why are neutrinos so difficult to detect?

*Hint 1.*

Study Section 14.2 of *The Cosmic Perspective.*

**ANSWER:**

- They have a tendency to pass through just about any material without any interactions.
- They are extremely rare.
- They have no mass.
- No one knows: this is the essence of the "solar neutrino problem."

This makes them difficult to detect because we need to see an interaction to know something passed through.

**Part R**

Which statement best describes what was called the solar neutrino problem?

*Hint 1.*

Study Section 14.2 of *The Cosmic Perspective.*

**ANSWER:**

- $p + p$ becomes $^2\text{H}$ + energy
- $6\text{H}$ becomes $1\text{He}$ + energy
- $4\text{H}$ becomes $1\text{He}$ + energy
- Individual protons are joined into long chains of protons.
This problem now seems to be resolved; the lower number of detections occurred because neutrinos can change type before they reach Earth. New detectors can find all neutrino types and confirm that the expected number are indeed present.

**Part S**

The light radiated from the Sun's surface reaches Earth in about 8 minutes, but the energy of that light was released by fusion in the solar core about __________.

**Hint 1.**

Study Section 14.2 of *The Cosmic Perspective*.

**ANSWER:**

- one hundred years ago
- a few hundred thousand years ago
- one thousand years ago
- three days ago

The energy takes a long time to make its way from the core to the surface (essentially because it bounces around so much within the solar interior), but once at the surface it travels through space to Earth at the speed of light.

**Part T**

What happens to energy in the Sun's convection zone?

**Hint 1.**

Study Section 14.3 of *The Cosmic Perspective*.

**ANSWER:**

- Energy is transported outward by the rising of hot plasma and sinking of cooler plasma.
- Energy is produced in the convection zone by thermal radiation.
- Energy is produced in the convection zone by nuclear fusion.
- Energy slowly leaks outward through the radiative diffusion of photons that repeatedly bounce off ions and electrons.

The rising of hot gas and falling of cool gas is an example of convection, which is why this region is called the convection zone.

**Part U**

What do sunspots, solar prominences, and solar flares all have in common?

**Hint 1.**

Study Section 14.3 of *The Cosmic Perspective*.

**ANSWER:**

No one understood how it could be possible for neutrinos to be produced in the Sun. It referred to the fact that neutrinos are extremely difficult to detect. Our understanding of fusion in the Sun suggested that neutrinos should be destroyed before they arrive at the Earth, yet neutrinos were being detected. Early experiments designed to detect solar neutrinos found them, but in fewer numbers than had been expected.
These magnetic fields can bind up or release vast amounts of energy, producing the phenomena of solar weather.

Part V
Which of the following is not a characteristic of the 11-year sunspot cycle?

**Hint 1.**
Study Section 14.3 of *The Cosmic Perspective*.

**ANSWER:**
1. The number of sunspots on the Sun at any one time gradually rises and falls, with an average of 11 years between the times when sunspots are most numerous.
2. The sunspot cycle is very steady, so that each 11-year cycle is nearly identical to every other 11-year cycle.
3. The likelihood of seeing solar prominences or solar flares is higher when sunspots are more common and lower when they are less common.
4. The Sun's entire magnetic field flip-flops at the end of each cycle (at solar minimum).

The sunspot cycle is not steady at all. Even the "11 years" is only an average, as cycle length varies between about 7 and 15 years. The number of sunspots at solar maximum also varies significantly, and it appears there have been times (such as the Maunder minimum) when the sunspot cycle virtually ceased to operate.

Part W
How is the sunspot cycle directly relevant to us here on Earth?

**Hint 1.**
Study Section 14.3 of *The Cosmic Perspective*.

**ANSWER:**
1. The sunspot cycle strongly influences Earth's weather.
2. Coronal mass ejections and other activity associated with the sunspot cycle can disrupt radio communications and knock out sensitive electronic equipment.
3. The brightening and darkening of the Sun that occurs during the sunspot cycle affects plant photosynthesis here on Earth.
4. The sunspot cycle is the cause of global warming.
5. The Sun's magnetic field, which plays a major role in the sunspot cycle, affects compass needles that we use on Earth.

This is the only direct effect of the sunspot cycle that has been recognized, though it may also have subtle influences in other ways, such as in some climate cycles.

**Visual Quiz**

**Part A**
The arrows in this diagram are meant to show how gravitational equilibrium works in the Sun. What do the different colors and different arrow lengths represent?

ANSWER:

- Green arrows represent gravity; red arrows represent the solar wind; longer arrows represent a stronger push or pull.
- Green arrows represent convection; red arrows represent radiation; longer arrows represent greater intensity.
- Green arrows represent gravity; red arrows represent pressure; longer arrows represent a stronger push or pull.
- Green arrows represent downward convection; red arrows represent upward convection; longer arrows represent stronger convection.

That is, gravity pulls inward while pressure pushes outward. The overlying weight becomes greater with depth, which is why the opposing forces become stronger.

Part B

What layer of the Sun are we seeing in this photo?

ANSWER:

- Corona.
- Photosphere.
- Radiation zone.
- Chromosphere.

The photosphere is the visible surface of the Sun.

Part C
The dark spots in this photo (such as the one indicated by the arrow) represent what we call:

ANSWER:
- solar prominences.
- Great Dark Spots.
- convection zones.
- coronal holes.
- sunspots.

Though they look small, remember that the Sun is huge; typical sunspots are larger than Earth.

**Part D**

Which photo shows Earth correctly scaled in comparison to the Sun?

ANSWER:
The Sun's diameter is more than 100 times Earth's diameter.

**Part E**

This photograph shows a small portion of the Sun's photosphere. What is going on in the bright regions (such as the bright region indicated by the arrow)?

**ANSWER:**
The bubbling pattern is caused by the underlying convection, and the bright spots are where hot gas is bubbling upward.

**Part F**

This X-ray image shows a loop of hot gas above the surface of the Sun. If we took a visible light photo that looked in the Sun's photosphere just under the two points where the loop of gas comes down (arrows), what would we find?

**ANSWER:**

- Bright prominences.
- Sunspots.
- Radiation zones.
- Coronal holes.

The loop is shaped by magnetic fields, and these loops generally are anchored to the strong magnetic fields of sunspots at each end.

**Part G**
Look again at the loop of hot gas in this X-ray image. Suppose we took another photo looking at the same place one hour later. What would we see?

**ANSWER:**

- The loop would have shot much higher up above the Sun's surface.
- The loop would have collapsed back down, so we would not see it anymore.
- The loop would look about the same as it does in this photo.
- The loop would have turned blue as the gas became hotter.

These loops are generally stable for weeks, since they are shaped by magnetic fields.

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**Part H**

What layer of the Sun are we seeing in this photograph, and in what wavelength band was it photographed?

**ANSWER:**

- Corona, photographed in X rays.
- Photosphere, photographed in visible light.
- Convection zone, photographed in infrared light.
- Chromosphere, photographed in visible light.
- Radiation zone, photographed in X rays.

You can tell it is the coronal because it extends so far out; the corona emits most strongly in X rays, so that's how you know it is an X-ray image.
Part I

What do the yellow regions represent in this photograph?

**ANSWER:**

- Coronal mass ejections.
- Regions where very hot gas is emitting a lot of X rays.
- Regions of unusually strong convection.
- Regions where the gas is emitting a lot of yellow visible light.

The yellow itself is arbitrary, since we cannot see X rays with our eyes; but the yellow clear indicates brighter emission, which therefore means more X rays since it is an X-ray image.

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Part J

Study this figure and its axis labels. What is this graph showing us?

**ANSWER:**

- The intensity of Sunlight varies significantly over time, and reached an unusually high peak around 1960.
- The number of sunspots on the Sun tends to increase and decrease with an approximately 11-year cycle.
- The Sun pulsates much like a beating heart, but with each beat taking about a decade.
- The latitude at which sunspots appear varies between 0 and 0.5 degrees.

It is a graph of the sunspot cycle over the past 100+ years.

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Problem 14.6

Part A

Why does nuclear fusion require high temperatures and pressures?

**ANSWER:**

Nuclear fusion is fusing of atoms together, atoms that are both of same charge meaning they repel each other, and for them to so called "stick together" it takes immense amount of energy. Biggest problem is getting atoms close...
Problem 14.7

Part A

What is the overall nuclear fusion reaction in the Sun? Briefly describe the proton-proton chain.

**ANSWER:**

Over all nuclear reaction in the Sun is conversion of Hydrogen into Helium (4:1) through nuclear fusion.

Proton-proton Chain:

Step 1: Two proton fuse to make a Deuterium nucleus.

Problem 14.9

Part A

Why has the Sun gradually brightened with time?

**ANSWER:**

Problem 14.53: The Color of the Sun

The Sun’s average surface temperature is about 5,800 K.

Part A

Use Wien's law (see Mathematical Insight Laws of Thermal Radiation) to calculate the wavelength of peak thermal emission from the Sun. Express your answer using two significant figures.

**ANSWER:**

\[ \lambda_{\text{max}} = 500 \text{ nm} \]

Part B

What color does this wavelength correspond to in the visible-light spectrum?

**ANSWER:**

- Red.
- Blue.
- Yellow.
- Green.
Part C
Why do you think the Sun appears white or yellow to our eyes?
ANSWER:

As we have seen from the continuous spectrum produced by the Sun, the wavelength max is at about 500nm, which is green but the curve of the Sun in quite flat which means its also all the other cours as well in less intensity which

Problem 14.50: The Lifetime of the Sun

The total mass of the Sun is about $2 \times 10^{30}$ kg, of which about 76% was hydrogen when the Sun formed. However, only about 13% of this hydrogen ever becomes available for fusion in the core. The rest remains in layers of the Sun where the temperature is too low for fusion.

Part A
Use the given data to calculate the total mass of hydrogen available for fusion over the lifetime of the Sun.

Express your answer using two significant figures.
ANSWER:

$m = 2.0 \times 10^{29}$ kg

Part B
The Sun fuses about 600 billion kilograms of hydrogen each second. Based on your result from part A, calculate how long the Sun’s initial supply of hydrogen can last. Give your answer in both seconds and years.

Express your answer using two significant figures.
ANSWER:

t = 3.3 \times 10^{17}$ s

Part C
Express your answer using two significant figures.
ANSWER:

t = 1.0 \times 10^{10}$ years

Part D
Given that our solar system is now about 4.5 billion years old, when will we need to worry about the Sun running out of hydrogen for fusion?

Express your answer using two significant figures.
ANSWER:

t = 5.9 billion years
Multiple Choice Question 5

Part A

What is the Sun made of?

ANSWER:

- 70 percent helium, 28 percent hydrogen, 2 percent other elements
- 98 percent hydrogen, 2 percent helium and other elements
- 100 percent hydrogen and helium
- 70 percent hydrogen, 28 percent helium, 2 percent other elements
- 50 percent hydrogen, 25 percent helium, 25 percent other elements