ASTRONOMY 20: STARS, GALAXIES, AND COSMOLOGY



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1: SKY PHENOMENA

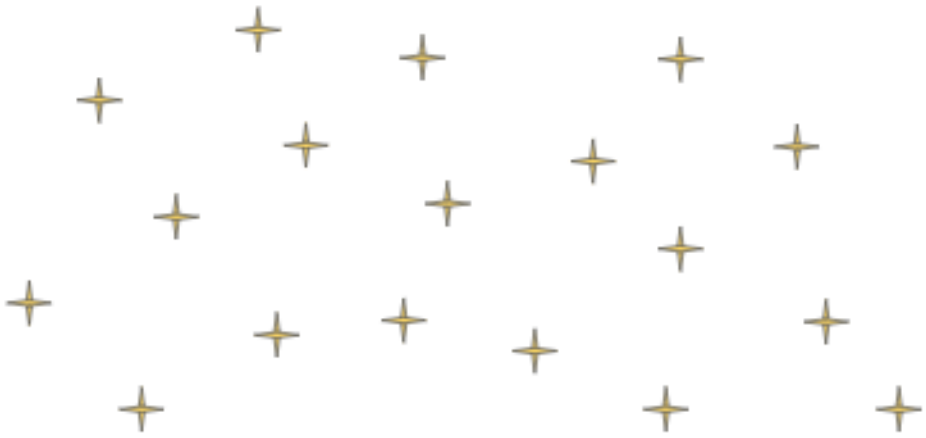
1.1: Horizon Coordinates
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1.1: Horizon Coordinates

1.1.1 Position of Objects in the Sky

Model

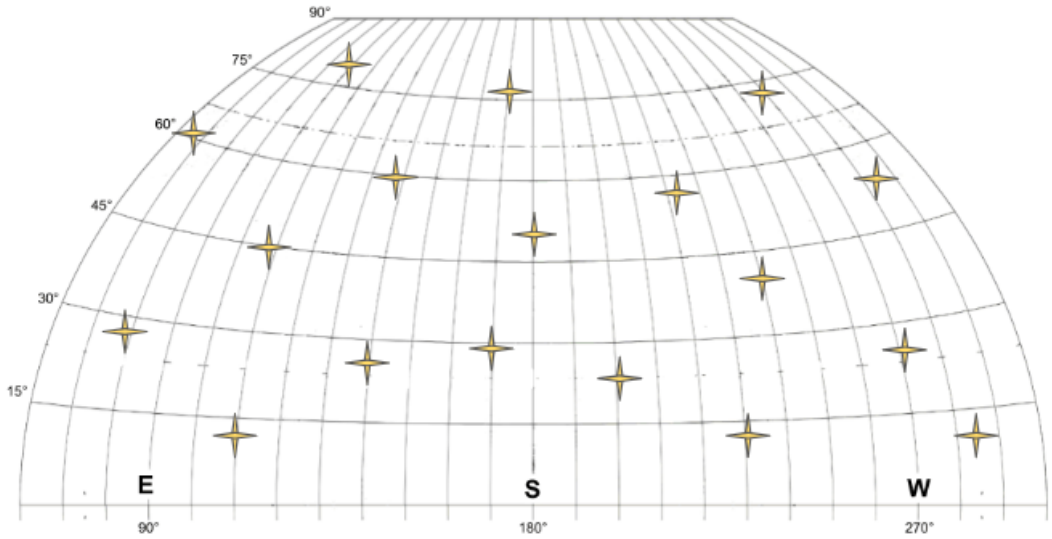


Star field model showing scattered stars used for locating and describing positions in the sky.

1. Choose a star in the sky. Do not point to it or give away its location.
2. Write instructions for how to locate that star.
3. Share your instructions with your group. Each member of the group should guess the location of your star. After everyone guesses, put a box around the actual star on your sky.
4. Discuss as a group:
    - What strategies or instructions worked well?
    - how you could make the process of identifying each other's star easier?
    - What was challenging?
5. If you were to make a constellation out of the pattern of stars near the star you have chosen, what would it look like? Draw your constellation on the image by drawing lines connecting the stars.

1.1.2 Altitude and Azimuth

Model



Altitude and azimuth grid with stars showing positions above the horizon and compass directions.

1. Choose a new star in the model but do not point to it.
2. Write instructions for how to locate that star.
3. Each person should guess the star by circling the star on the other person's sky.
4. After everyone guesses, put a box around the actual star on your sky.
5. Discuss as a group:
    - Was this easier, harder, or the same?
    - Why?
6. In a **Planetarium** or using planetarium software (eg, *Stellarium*), choose five stars in different parts of the sky. For each star, identify:
    - **Cardinal Direction** (eg, North or South-East) and **Azimuth**
    - **Altitude**
    - **Apparent Brightness** (very bright, very dim, etc)
    - **Any other identifiers** (characteristics about the star, its position, color, etc)
7. Discuss the questions as a group, then respond in complete sentences:
    1. Why are Cardinal Directions (**Azimuth**) and **Altitude** useful concepts for astronomical observation?
    2. How else can astronomers communicate information about a star to help others locate the same star?

1.1.3 Changing Sky

Model

In a **Planetarium** or using planetarium software (eg, *Stellarium*), observe the changing sky at 300x speed.

1. What do you notice about the position of these stars?
2. Are there any patterns you can identify?
3. In which parts of the sky do stars rise? In which parts of the sky do stars set?
4. Do any stars remain still?

1.1.4 Polaris and the Circumpolar Region

Model

In a **Planetarium** or using planetarium software (eg, *Stellarium*), locate the **North Star (Polaris)**

1. What is the **Azimuth** and **Altitude** of this star? Do either change over the course of the night?
2. How do stars appear to move in relation to the North Star?
3. The **Circumpolar Region** is the region of stars in the sky that do not set over the course of a 24 hour cycle. What is the shape of this region and how do its measurements/size relate to the **Azimuth** or **Altitude** of **Polaris**?

1.1.5 Effect of Latitude on Polaris and the Circumpolar Region

Model

In a **Planetarium** or using planetarium software (eg, *Stellarium*), locate the **North Star (Polaris)**. Chose several different locations on earth (different **latitudes** and **longitudes**) and record the **Altitude** and **Azimuth** of Polaris

1. Identify a pattern (no effect is a type of pattern) between **latitude/longitude** and **Altitude/Azimuth**
2. Identify a pattern (no effect is a type of pattern) between **latitude/longitude** and **the size and location** of the **Circumpolar Region**.

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1.2: Apparent Motion

1.2.1 Star Trails: Sky View

Model

Open the simulation and select **Sky View** at https://astro.unl.edu/smartphone/StarTrails/

1. What is the current **latitude**?
2. Which direction do you have to face to see objects rise? At what angle do they rise?
3. Which direction do you have to face to see objects set? At what angle do they set?
4. Which direction do you have to face to see the top of the motion arc?
5. Do all objects rise at the same azimuth?
6. Do all objects set at the same azimuth?
7. What changes when you change the latitude?
8. Draw the paths when you look in each direction and write a one-sentence description of the paths objects take in that sky.

East Description:	**West** Description:
North Description:	**South** Description:

1.2.2 Star Trails: Horizon Diagram

Model

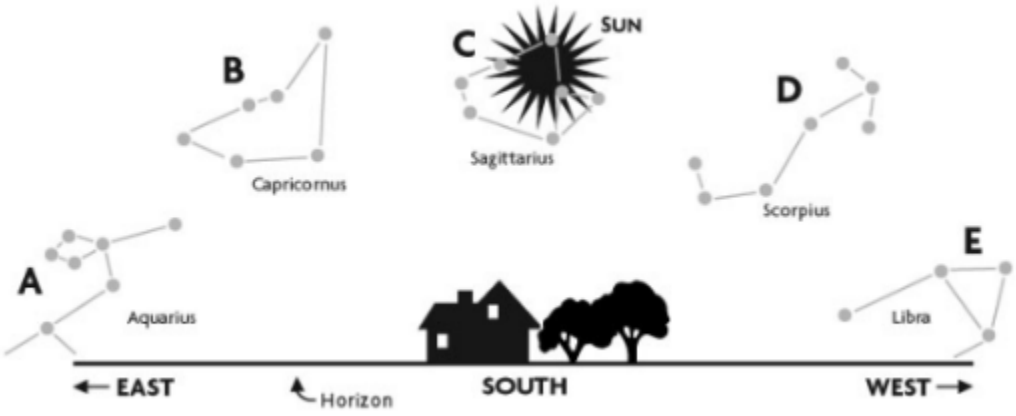
Open the simulation and select **Horizon Diagram** at https://astro.unl.edu/smartphone/StarTrails/

The red line represents a meridian line with the **North Celestial Pole** on one end and the **South Celestial Pole** on the other end. The blue line represents the **Celestial Equator**.

1. Adjust the latitude slider. How does the position of the **North Celestial Pole** shift relative to the horizon (flat ground) based on latitude? See if you can be specific and use exact numbers in your response.
2. Adjust the latitude slider. How does the position of the **Celestial Equator** shift relative to the horizon (flat ground) based on latitude? See if you can be specific and use exact numbers in your response.
3. Describe how objects appear to move on this model.
4. Track an individual star that is south of the celestial equator: Does the star always exist or does it eventually disappear? Are there any times where the star is in a position such that the person on the ground would not be able to see it? Explain your reasoning.

1.2.3 Looking South

Model



Southern sky horizon diagram showing constellations rising and setting across the sky.

Image Credit: Astronomy Interactives from the Astronomy Education Department at the University of Nebraska-Lincoln (https://astro.unl.edu/interactives/)

1. Which constellation is currently rising in the image? How do you know?
2. Which constellation is currently setting in the image? How do you know?
3. Which constellation was the first to rise on this day? Which constellation was the last to rise on this day? Label this on the diagram and explain your reasoning.

4. Is the Sun closer to rising, setting, or directly in between rising and setting? Based on your response, estimate the time of day.
5. Draw an arrow on each constellation to show the direction it is currently moving.

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6. On the horizon below, draw the Sun and write the constellation names (you do not need to draw them) where you think they will be at the listed times.

6AM

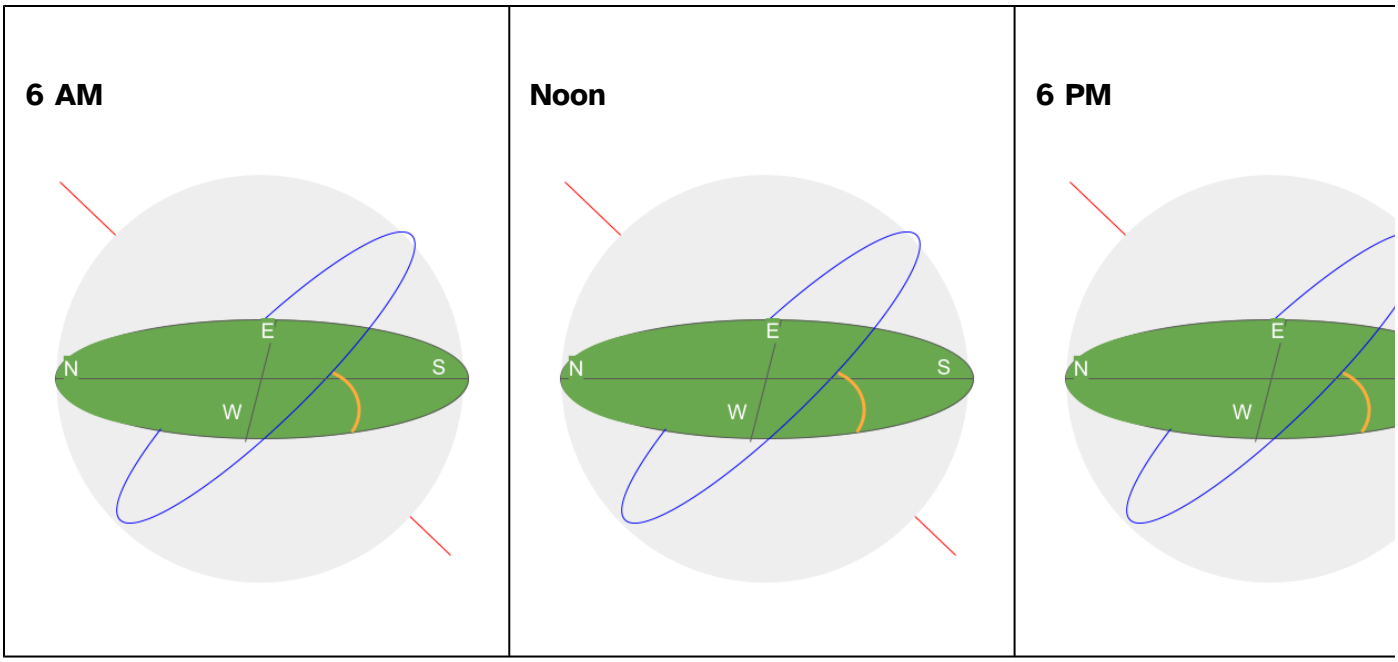


6PM



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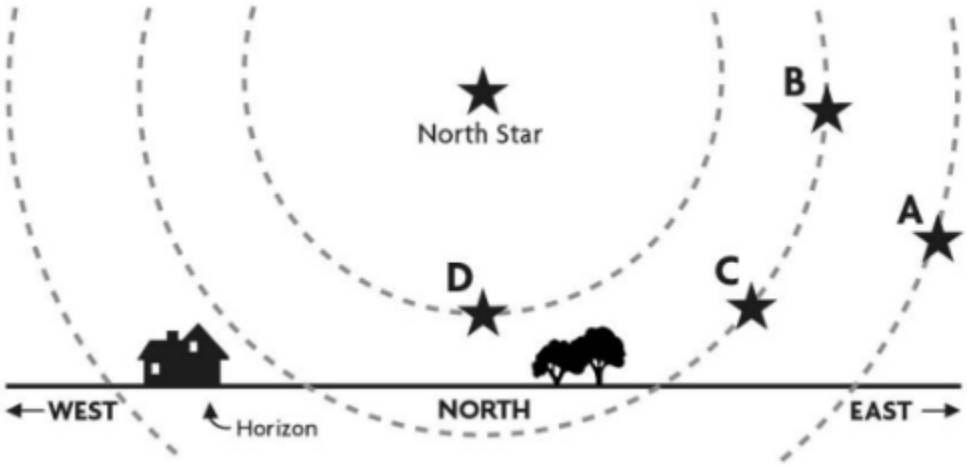
7. Draw the Sun and list the constellations based on their letters at the listed times on the celestial sphere model.



1.2.4 Looking North

Model

Examine the model below. The dashed lines show the path those stars will take. On each star, draw an arrow to show the direction it is moving.



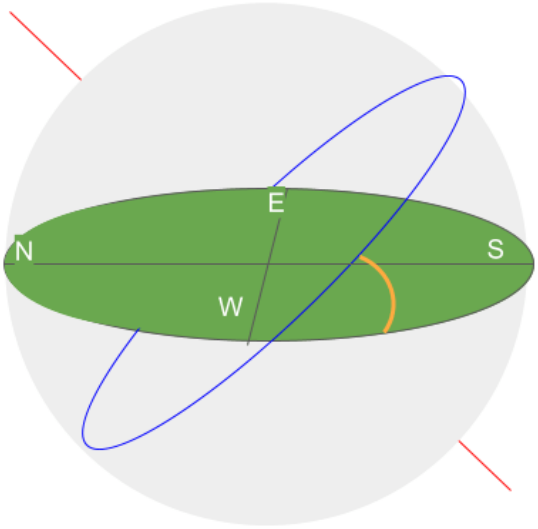
Northern sky diagram showing stars moving around the North Star with dashed motion paths.

Image Credit: Astronomy Interactives from the Astronomy Education Department at the University of Nebraska-Lincoln (https://astro.unl.edu/interactives/)

1. Which star(s), if any, are currently rising? Which star(s), if any, are currently setting? Explain your reasoning.

2. Rank the stars based on how much time they spend above the horizon in a 24-hour period (1 = most time above the horizon).
3. How does the proximity to the North Star relate to how long a star is above the horizon?
4. Which star will be the first to set? Explain your reasoning.
5. On the diagram below, draw the stars based on where you think they will be 12 hours later.
6. Draw the North Star and stars A–D at their positions that you just drew for question 6 on the celestial sphere model below.





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1.3: The Zodiac - Seasonal Stars

1.3.1 Zodiac and the Sun

Model

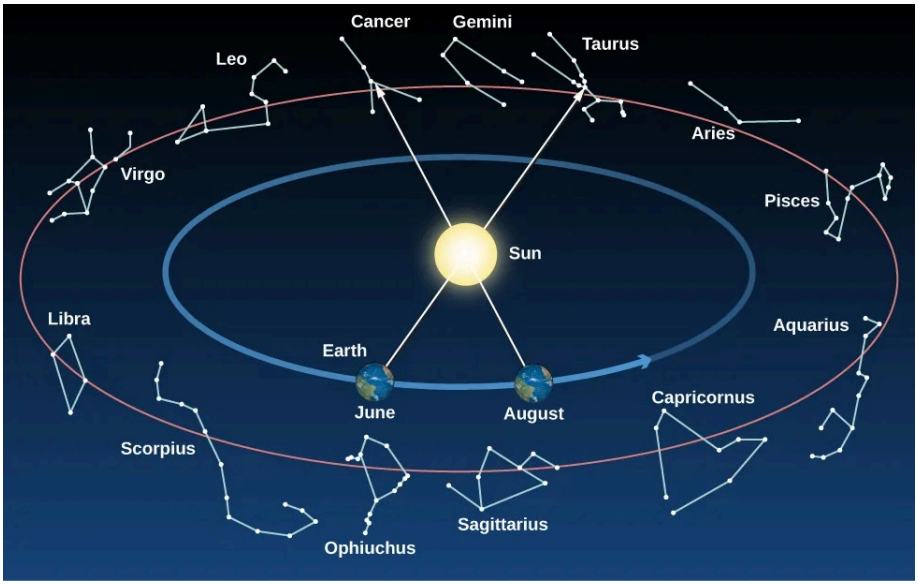
In a **Planetarium** or using planetarium software (eg, *Stellarium*), examine the sky and record your observations in the table below. For the last row, choose any date you want (eg, a birthday):

Date	Location of Sun at Noon

1. At noon, is the Sun always in the same constellation throughout the year?
2. How long does the Sun remain in a particular constellation?
3. Based on your answer above, how many zodiac constellations should there be? Explain your reasoning.

1.3.2 Zodiac in a Yearly Cycle

Model



The Zodiac make a ring around Earth's orbit around the sun. Astrological "sun sign" is constellation across the sun from Earth.

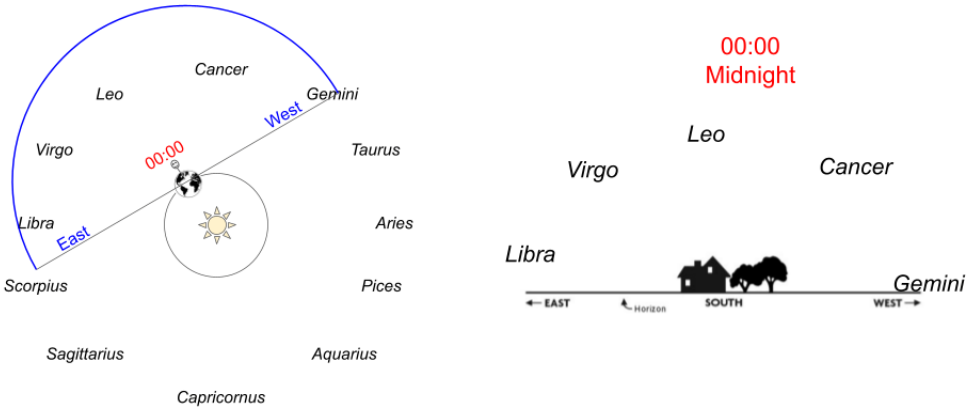
Image Credit: OpenStax Astronomy 2e (https://openstax.org/details/books/astronomy-2e)

1. When someone is a **Cancer**, is the earth **next to Cancer** or **opposite Cancer** on the other side of the sun?
2. When someone is a **Taurus**, is the earth **next to Taurus** or **opposite Taurus** on the other side of the sun?
3. On your birthday, can you see your zodiac sign? Explain your reasoning.
4. Constellations that are in the middle of the arc that represents your sky are highest in the sky. At what time of day, on your birthday, is your zodiac sign at its highest point in the sky? Explain your reasoning.
5. Work with your group to label the **Earth Locations** by month on one of the images in the model, based on your knowledge of your assigned zodiac signs and your birth dates.
6. Identify which constellations are in your midnight sky on your birthday. Draw them out on the sky view.

Image needed here with Alt Text:
Sky view template for drawing midnight constellations visible from Earth on a selected date.

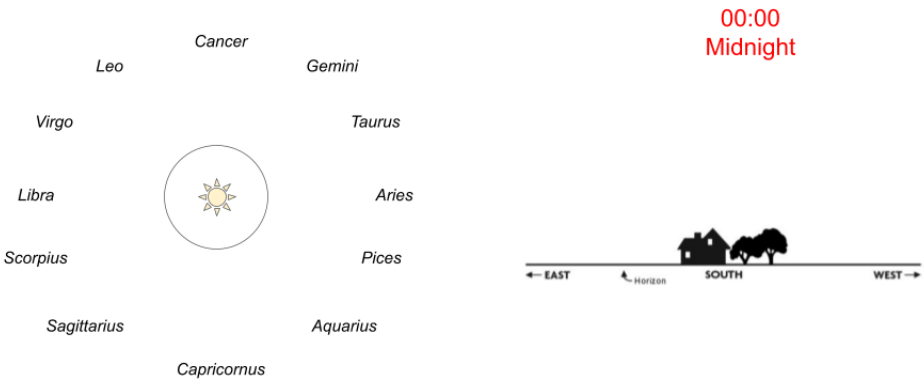
1.3.3 Zodiac in the Night Sky

Model



The Zodiac make a ring around Earth's orbit around the sun with midnight sky shown as the half opposite the sun.

1. Describe how to determine your Midnight Sky at different months of the year using the Zodiac chart. Consider:
    1. Where on the Earth model should the person be at midnight?
    2. What parts of the sky are **not blocked** by Earth?
2. Identify which constellations are in your midnight sky on your birthday. Show the Earth location and write the Zodiac constellation names on the sky view template.



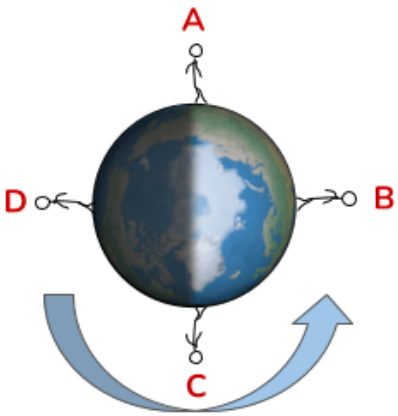
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1.4: Seasonal Sun Position

1.4.1 Time of Day

Model

This is a view of the Earth where we are looking down at the North Pole. The Earth spins counterclockwise, carrying the person with it.





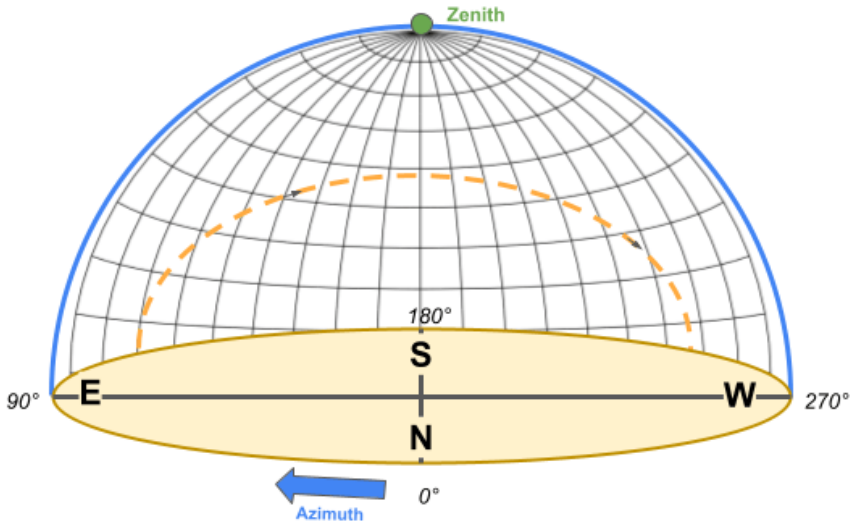
Earth viewed from above the North Pole with people A–D and the Sun showing day and night sides.

1. Which person(s) (A, B, C, or D) is/are experiencing day time? Explain your reasoning.
2. Which person(s) (A, B, C, or D) is/are experiencing night time? Explain your reasoning.
3. Which person is experiencing each time of day? Label the times next to the letters.
    - 6AM
    - Noon
    - 6PM
    - Midnight

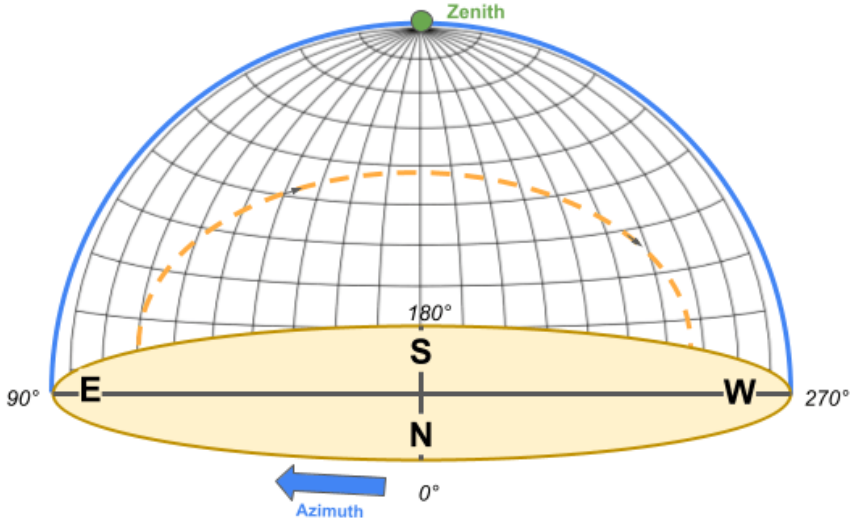
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4. Draw a sun figure on the arc to represent the location of the sun in the local view of the sky at each time. Explain your reasoning under the figure.

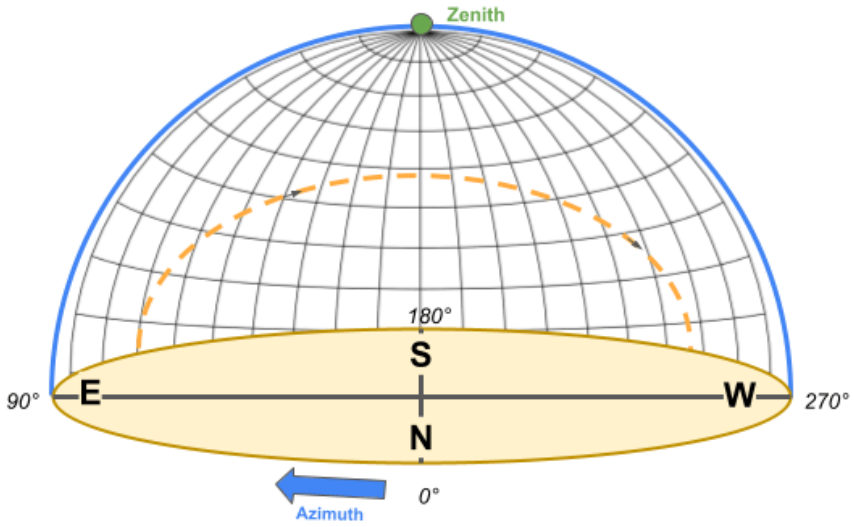
6AM


Zenith
180°
S
90°
E
W
270°
N
0°
Azimuth

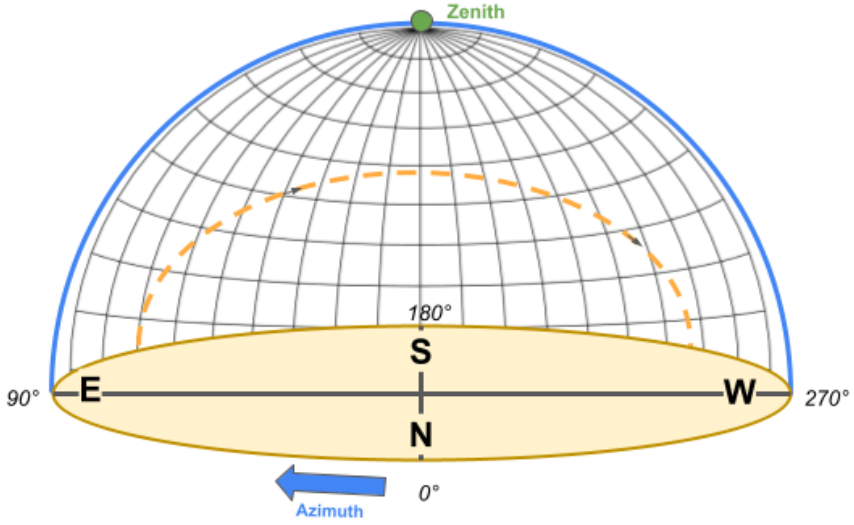
Noon


Zenith
180°
S
90°
E
W
270°
N
0°
Azimuth

6PM



Midnight



5. At what time is the position of the sun at its highest point in the sky? What direction do you need to look to see the sun at this time?
6. At sunrise, what direction do you need to look to see the sun?
7. At sunset, what direction do you need to look to see the sun?
8. At both sunrise and sunset, draw a dashed circle on the sky to show the location of the sun one hour later (7AM and 7PM). Label those dashed circles with their times. Then, add these people as stick figures to the original model and label them with their times.

1.4.2 Solar Altitude by Latitude

Model

Use the simulation as a source of evidence for this activity. The sun rays show the position of the sun at noon on the specified day of the year. Open the simulation at:

https://astro.unl.edu/classaction/animations/coordsmotion/eclipticsimulator.html

1. Set the month to March. Adjust the latitude to the values in the table below and record what you observe at that latitude.

Latitude and Altitude of the Sun

Latitude	Altitude of the Sun
20° N	
40° N	
60° N	
20° S	
40° S	
60° S	

2. How does your latitude affect the altitude of the sun that you observe at noon in the month of March?
3. Construct an equation for the altitude of the sun (h) and show that your equation works with two different entries in the table above.

$h =$

1.4.3 Seasonal Solar Altitude

Continue to use the simulation at:

https://astro.unl.edu/classaction/animations/coordsmotion/eclipticsimulator.html

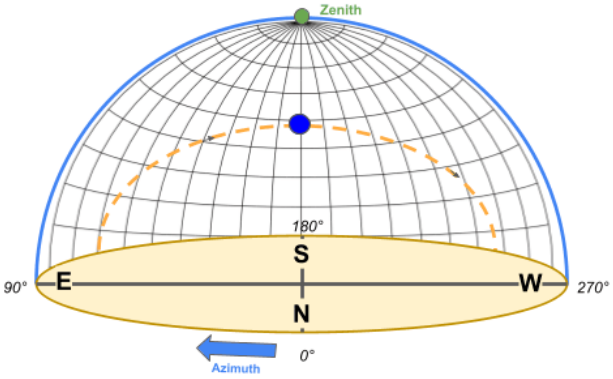
1. Set your latitude to 40° N. What does your equation say the solar altitude should be at noon?
2. Change the month. Is your equation still valid? If not, can you find another month (besides March) that your equation is valid for?
3. Change the month and fill in the table based on your observations. Identify how many degrees higher (+) or lower (-) the measured altitude is compared to your calculated solar altitude.

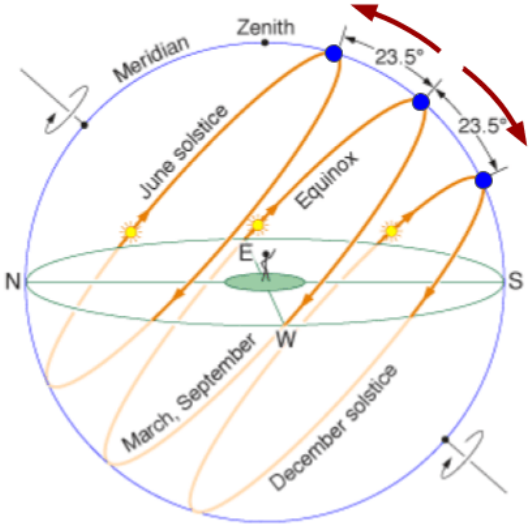
Seasonal Solar Altitude Observations

Month	Measured Altitude	Degrees +/- Predicted
December		
March		
June		
September		

4. Summarize your results. What pattern do you notice throughout the year? How might this relate to seasons (Summer, Fall, Winter, Spring)?

Summary





The altitude of the sun at noon from your latitude changes throughout the season because the Earth is tilted.

The measured altitude is given by the equation:

$h =$

The seasonal tilt ranges from ° to °.

1.4.4 Seasonal Light

Model

Continue to use the simulation at:

https://astro.unl.edu/classaction/animations/coordsmotion/eclipticsimulator.html

1. Set the latitude to 37° N. Switch back and forth between December and June and fill out the table to compare the differences about the sun's rays during these two months.

Seasonal Light Comparison

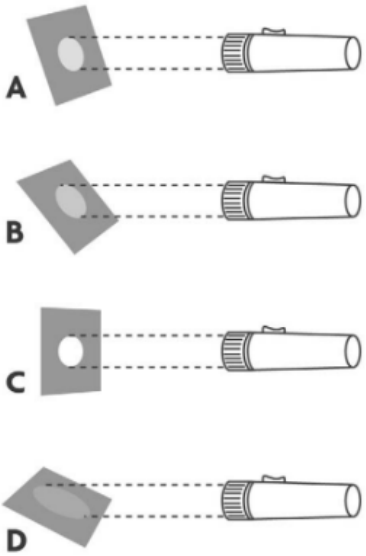
	December	June
Altitude of the sun is (higher / lower)		
Rays are (more vertical / more horizontal)		
Rays are (closer together / farther apart)		
Person is (closer / farther) from shadowed part of Earth		

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1.5: The Reason for the Seasons

1. Seasons

1.5.1 Solar Brightness and Light Angle



Five light beam examples A–E showing different light angles and illuminated areas on a surface.

Image Credit: Astronomy Interactives from the Astronomy Education Department at the University of Nebraska-Lincoln (https://astro.unl.edu/interactives/)

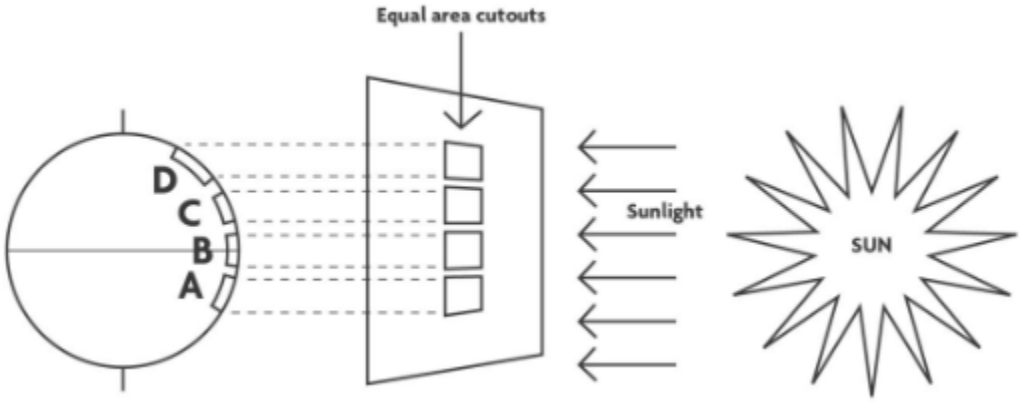
1. Give each lettered example a ranking for: Brightness (1 is brightest), illuminated area (1 is greatest), and angle between light and paper (1 is greatest angle).

Solar Brightness and Light Angle Rankings

Example	Brightness	Illuminated Area	Angle
A			
B			
C			
D			

2. Summarize the patterns you saw above: How does the angle between the ground and a line from the Earth to the sun affect how bright sunlight is on that part of the ground?

1.5.2 Light Angle and Earth Position



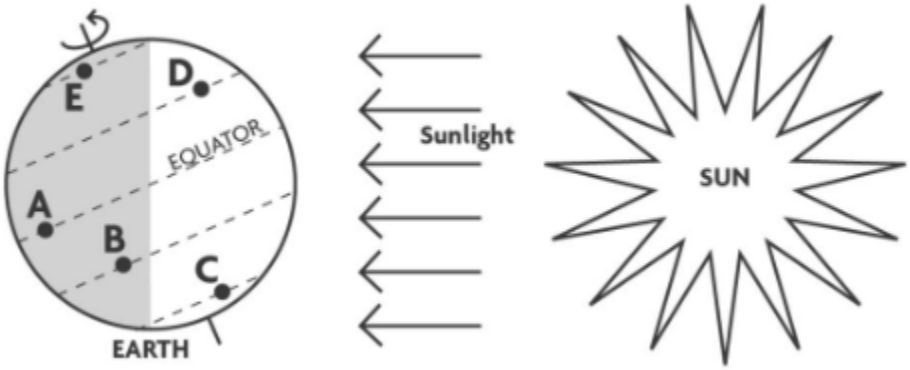
Earth diagram with equal light cutouts showing how sunlight spreads across different latitudes.

Image Credit: Astronomy Interactives from the Astronomy Education Department at the University of Nebraska-Lincoln (https://astro.unl.edu/interactives/)

1. Examine the area cutouts: How do the areas compare? Based on your response and the patterns in the previous model, how should the amount of light in each cutout compare?
2. Examine the portions of the Earth that receive light from each cutout: How do the areas along the Earth compare? Based on your response and the patterns in the previous model, how should the brightness of light on each portion of the Earth compare?
3. Summarize: What parts of the Earth receive the most light? What parts of the Earth receive the least light?
4. Interpret: What parts of the Earth are warmer? What parts of the Earth do you think are colder? Justify your responses with the patterns you identified in the previous questions.

1.5.3 Seasonal Daylight

Model



Tilted Earth model with latitudes A–E showing daylight and nighttime portions of rotation paths.

Image Credit: Astronomy Interactives from the Astronomy Education Department at the University of Nebraska-Lincoln (https://astro.unl.edu/interactives/)

1. Each letter represents a latitude. For the time of the year shown, estimate the percentage of time that position is in daylight

and night, based on the fraction of the dashed line that is on the illuminated and dark portions of the Earth model.

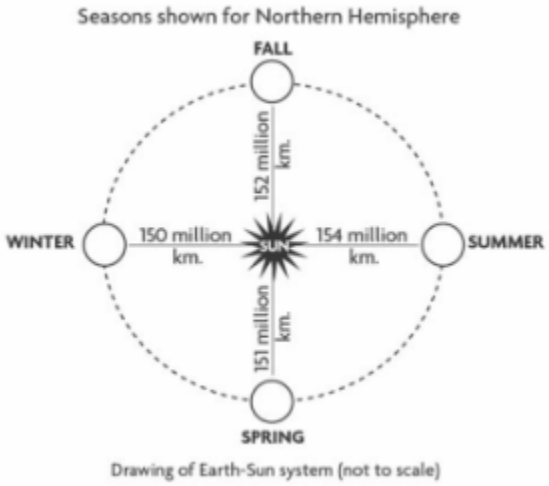
Seasonal Daylight Estimates

Latitude	Daylight %	Night %
A		
B		
C		
D		
E		

2. Which portion of the Earth (top or bottom) is tilted more towards the sun?
3. For the part of the Earth (top or bottom) that you identified in the previous question, do latitudes near that point experience more daylight or more night?
4. Which part of the Earth (top or bottom) do you think spends more time heating up during a 24-hour period? Explain your reasoning.
5. Which part of the Earth (top or bottom) do you think is experiencing summer? Explain your reasoning.

1.5.4 Light Angle and Earth Position

Northern Hemisphere Season	Southern Hemisphere Season	Earth-Sun Distance (km)
Spring	Fall	151 million
Summer	Winter	154 million
Fall	Spring	152 million
Winter	Summer	150 million



Earth orbit diagram showing seasonal positions and varying Earth–Sun distances.

Image Credit: Astronomy Interactives from the Astronomy Education Department at the University of Nebraska-Lincoln (https://astro.unl.edu/interactives/)

6. Would you expect the Earth to be warmer when it is closer or farther from the sun? Explain your thinking.
7. During which season is the Earth closest to the sun? Is that a warm or cold season?
8. During which season is the Earth farthest from the sun? Is that a warm or cold season?
9. Do you think the distance between the Earth and the sun causes the seasons? Explain your reasoning using evidence from this model.
10. Consider this student conversation and identify whether you agree or disagree with each student:

    Student A: The distance between the Earth and the sun cannot be the cause of the seasons because the Earth is 4 million kilometers closer to the sun in the winter, when it is colder. That doesn't make sense because being closer should make the Earth warmer. The cause of the seasons must be related to the tilt of the Earth, not the distance between the Earth and the sun.

Student B: I agree that the tilt is what causes the seasons, but I think it is related to distance. When the Northern Hemisphere of the Earth is tilted towards the sun, it is closer to the sun than the Southern Hemisphere. So distance does play a part.

Student C: I disagree. The Northern Hemisphere might be closer to the sun than the Southern Hemisphere when it is summer in the Northern Hemisphere, but the whole planet is farther away. So it must be the way the tilt affects how the light reaches us, not the change in distance caused by the tilt.

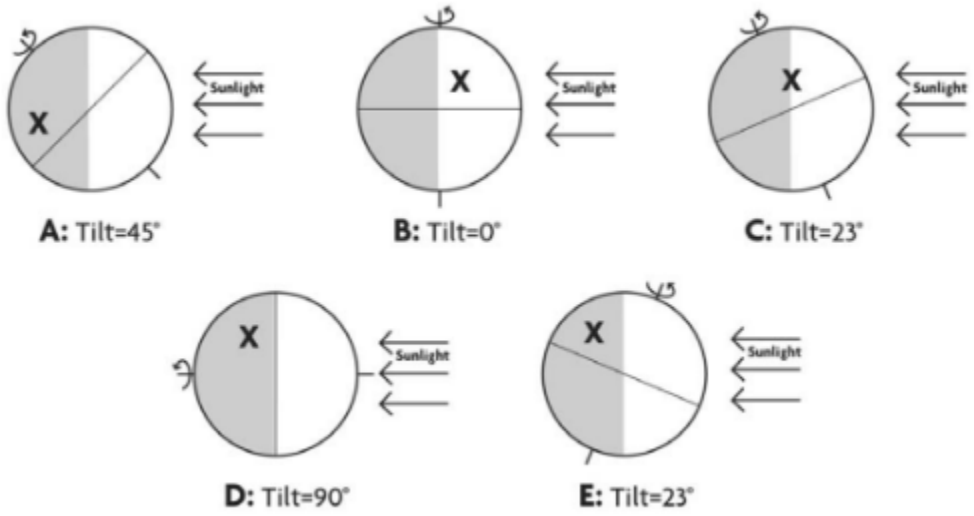
Summary

Explain how each of the following do or do not affect the seasons:

- Distance between Earth and Sun
- Sunlight Angle
- Amount of Daylight Hours

Application

Imagine a person is at the "X" on each figure. Rank the different examples in terms of: Hours of daylight and sun angle. Then rank them in terms of greatest daytime temperature.



Multiple Earth diagrams with person marked X for comparing daylight, sun angle, and temperature.

Image Credit: Astronomy Interactives from the Astronomy Education Department at the University of Nebraska-Lincoln (https://astro.unl.edu/interactives/)

Application Rankings

Example	Hours of Daylight Rank	Sun Angle Rank	Greatest Daytime Temperature Rank
A			
B			
C			
D			

Example	Hours of Daylight Rank	Sun Angle Rank	Greatest Daytime Temperature Rank
E			

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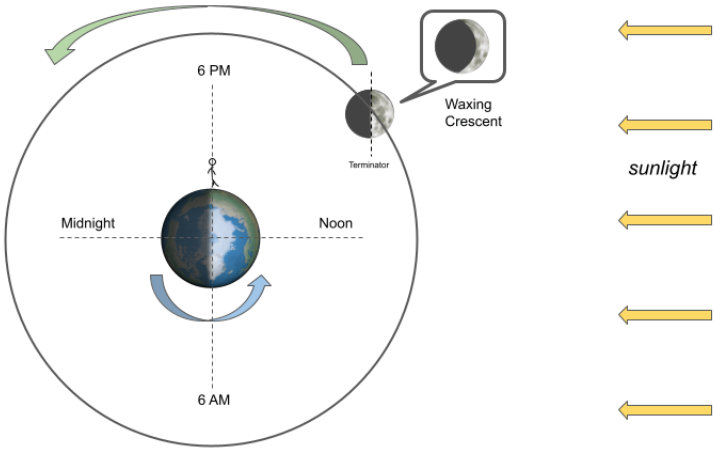
1.6: Monthly Cycles - Lunar Phases

1. Moon Phases

1.6.1 Illuminated Surface

Model

Examine the moon as shown on its orbit around the Earth:



Moon as Waxing Crescent orbiting Earth with sunlight showing illuminated and dark halves of the Moon as well as Moon appearance from Earth.

1. What percent of the moon is dark? What percent is illuminated?
2. Which part of the moon is dark? How does this relate to the direction of the sunlight?
3. What is the name of the line separating light and dark on the moon?
4. Look at just the portion of the moon that is facing Earth, just inside the circle of its orbit: Is that portion of the moon more dark or more illuminated?

Examine the moon in the dialogue box, which represents how it is seen from Earth.

5. What percent of the moon as seen from Earth is dark? What percent is illuminated?
6. Which side (left or right) of the moon is dark? Which side is light?

1.6.2 Identifying Moon Phases

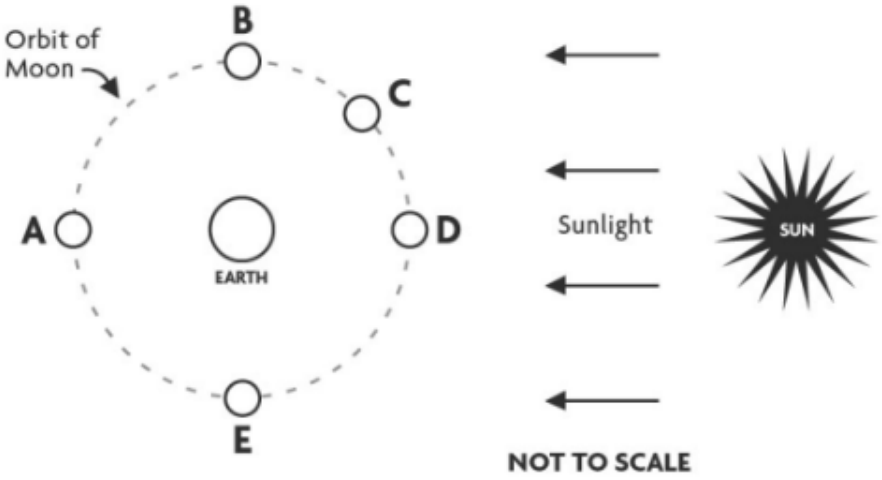
Model

The model below shows the moon in different positions around its orbit.

Mark up the diagram to include the following:

- Add terminators to the Earth and moon in each moon position.

- Shade in the side of the moon that is not illuminated by the sun.
- Imagine you are looking at the moon from Earth. Write “L” next to the left side of the moon and write “R” next to the right side of the moon from your perspective on Earth.



Earth and Moon orbit diagram with Moon positions A–E for analyzing lunar phases.

Image Credit: Astronomy Interactives from the Astronomy Education Department at the University of Nebraska-Lincoln (https://astro.unl.edu/interactives/)

1. Rank the moons (A–E) based on how much of the moon, as viewed from Earth, is illuminated (1 being most illuminated).

Moon Illumination Ranking

Moon Position	Rank
A	
B	
C	
D	
E	

2. Sketch what you expect the moon to look like from Earth at each position.

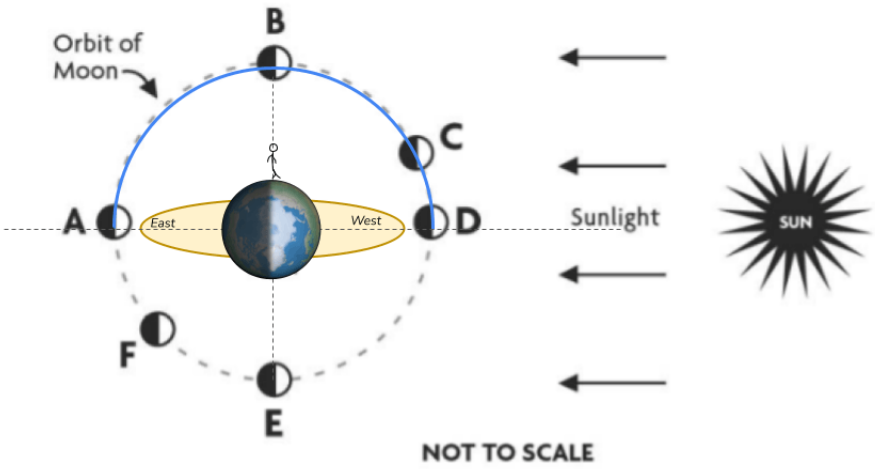
Moon Phase Sketches

A	B	C	D

3. Explain how you determined the moon phases.

1.6.3 Moon Rise and Set Times

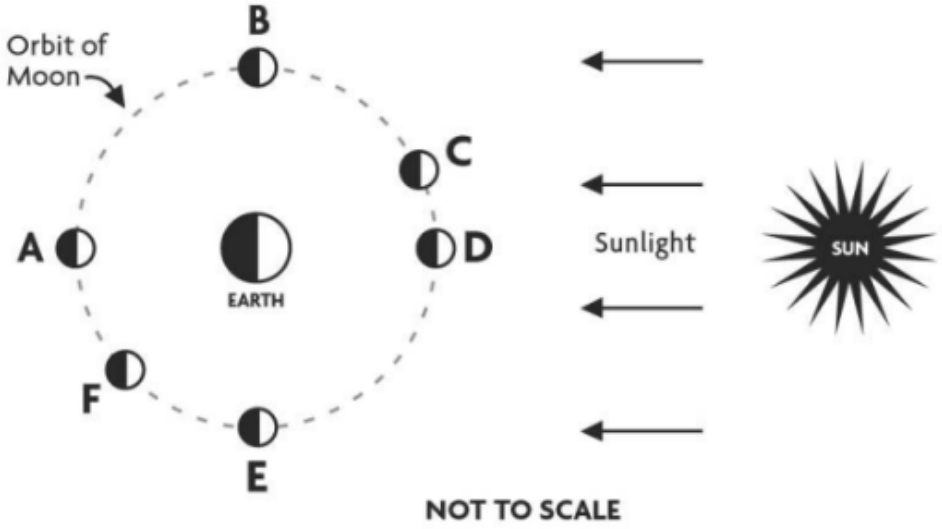
Model



Earth with observer and Moon positions A–F used to determine moonrise and moonset times.

Image Credit: Image adapted from Astronomy Interactives from the Astronomy Education Department at the University of Nebraska-Lincoln (https://astro.unl.edu/interactives/)

1. What time is it for the person shown on Earth?
2. Which moon (A–F) is on your western horizon? Does that mean that moon would be rising or setting?
3. Which moon (A–F) is on your eastern horizon? Does that mean that moon would be rising or setting?
4. Based on your answers to the previous two questions, which moon would be at its highest point in the sky, equal distance between rising and setting?
5. Where on the Earth would the person need to be for Moon F to be rising? Draw the person at this location and identify what time of day it must be for that person. Sketch the East-West horizon on the figure. Then answer the following quesitons for this new person-location:
    1. Which moon would have set most recently for the person in the position you drew above? Explain your reasoning.
    2. Which moon will be the next to rise? At what approximate time will it rise? Explain your thinking.



Earth with observer and Moon positions A–F used to determine moonrise and moonset times.

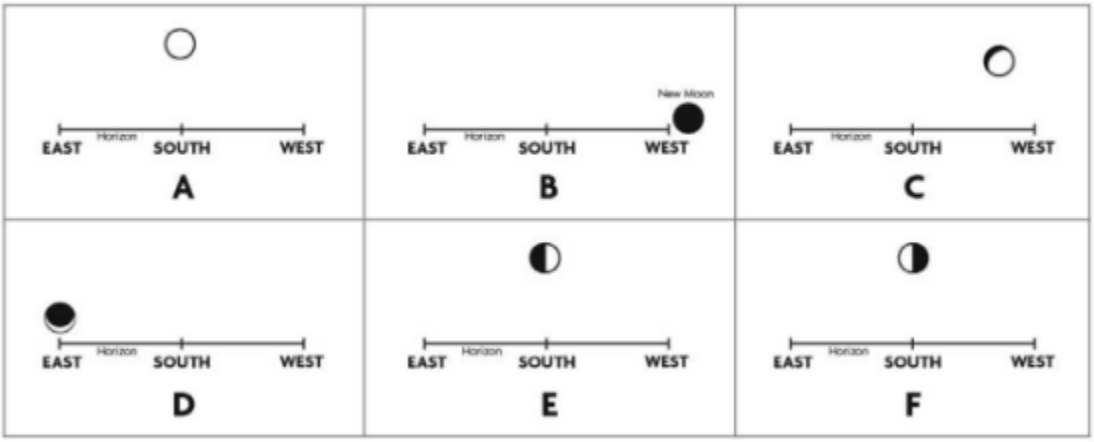
Image Credit: Astronomy Interactives from the Astronomy Education Department at the University of Nebraska-Lincoln (https://astro.unl.edu/interactives/)

Application

Your instructor will assign you one of the following horizon sky views.

Circle your assigned view and complete the following:

- Draw a model of the Earth, the moon in its orbit around the Earth, the Sun and sunlight for the moon shown in the assigned horizon.
- Draw a stick figure to show where around the Earth the person is to see this sky view.
- Identify the approximate time shown in the sky view.
- Identify the rise and set time for that moon.



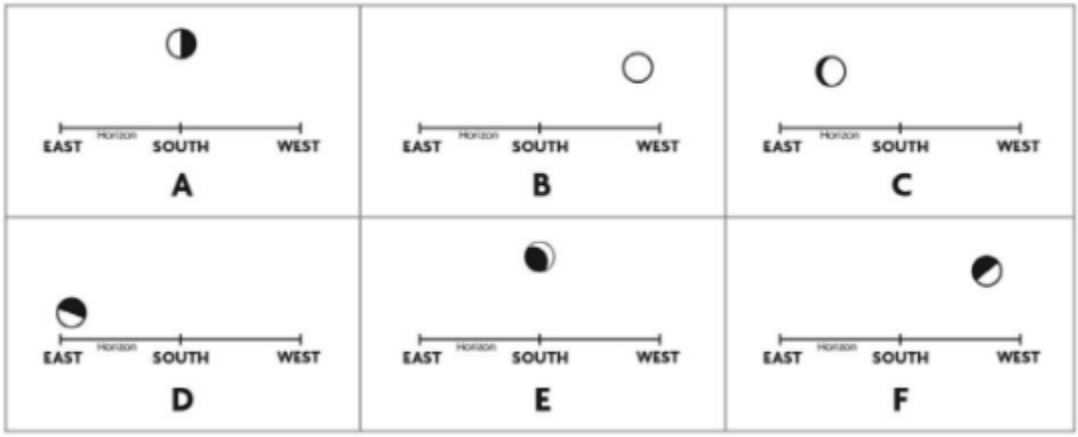
Multiple horizon sky views showing Moon phases for Earth–Moon–Sun modeling activity.

Image Credit: Astronomy Interactives from the Astronomy Education Department at the University of Nebraska-Lincoln

(https://astro.unl.edu/interactives/)

Application Response Area

Assigned Horizon View	Approximate Time	Moon Rise Time	Moon Set Time



Multiple horizon sky views showing Moon phases for Earth–Moon–Sun modeling activity.

Image Credit: Astronomy Interactives from the Astronomy Education Department at the University of Nebraska-Lincoln (https://astro.unl.edu/interactives/)

Application Response Area

Assigned Horizon View	Approximate Time	Moon Rise Time	Moon Set Time

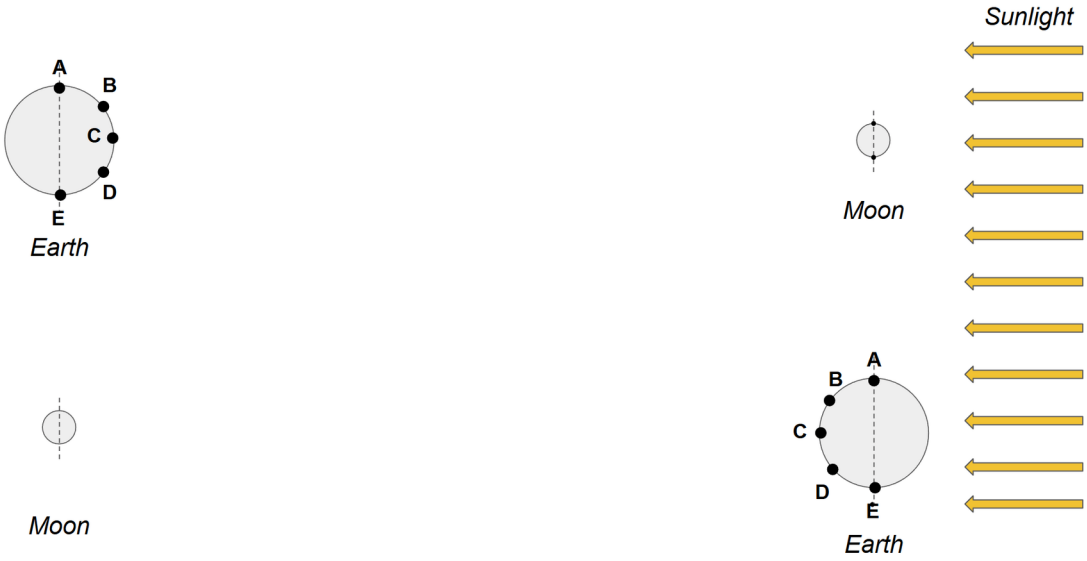
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1.7: Eclipses

1.7.1 Basic Shadows

Model

The model below shows sunlight coming in from the right. On top, the Moon is between the Earth and the sun and will cast a shadow on the Earth. On the bottom, the Earth is between the sun and the moon and will cast a shadow on the moon.



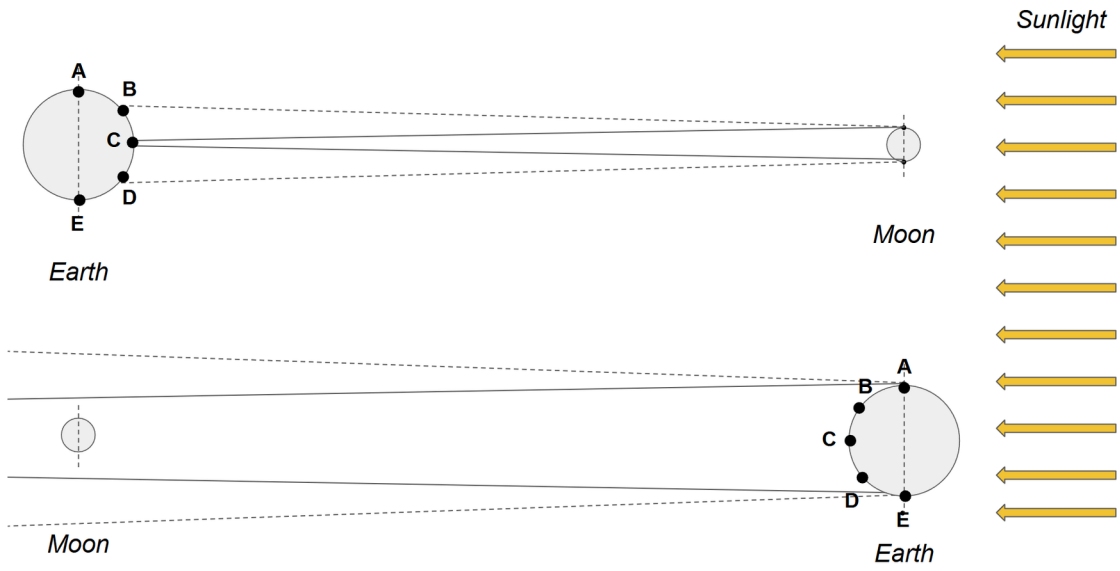
Two models show the Moon and Earth cast shadows on each other with sunlight from the right.

1. Mark up the Model
    1. Shade in the portion of the Moon and Earth that should be dark, based on the location of the sun (to the right of both objects).
    2. On the top model, draw a straight, horizontal line from each of the dots on the top and bottom of the moon to the Earth.
    3. On the bottom model, draw a straight, horizontal line from each of the dots on the top and bottom of the Earth to (or just past) the Moon.
    4. Shade in any additional portion of the Earth or Moon that should be dark, based on the shadows cast by each object
2. Examine your model
    1. Are many people on Earth in the moon's shadow? Or is there just a small portion of Earth that experiences this event? Which people (A-E) would experience this event?
    2. Are there many people on Earth that see the Earth's shadow on the moon? Or is there just a small portion of Earth that can see this event? Which people (A-E) would experience this event?
3. Are you more likely to see a solar eclipse (be in the moon's shadow on Earth) or see a lunar eclipse (see the Earth's shadow on the moon)? Make a claim and provide clear evidence and reasoning from your model.

1.7.2 Umbra and Penumbra

Model

Based on the physical size of the Sun, Earth, and Moon and their distances between each other, partial and full shadows are possible. The solid line represents the **umbra** which is a full shadow (no light). The dashed line represents the **penumbra** which is a partial shadow (some light is blocked but some light is not).



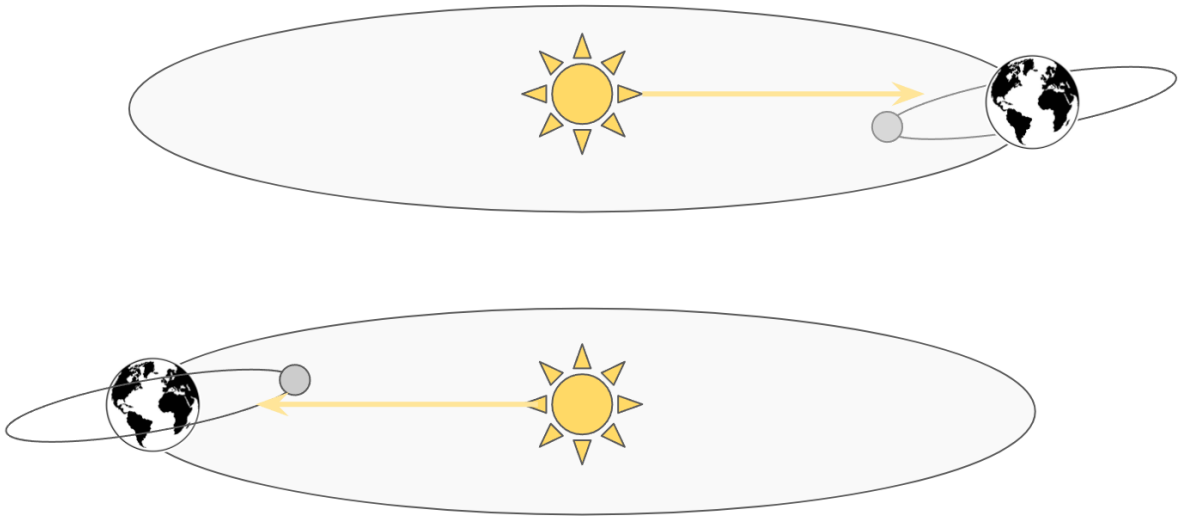
Two models show the Moon and Earth cast their umbral and penumbral shadows.

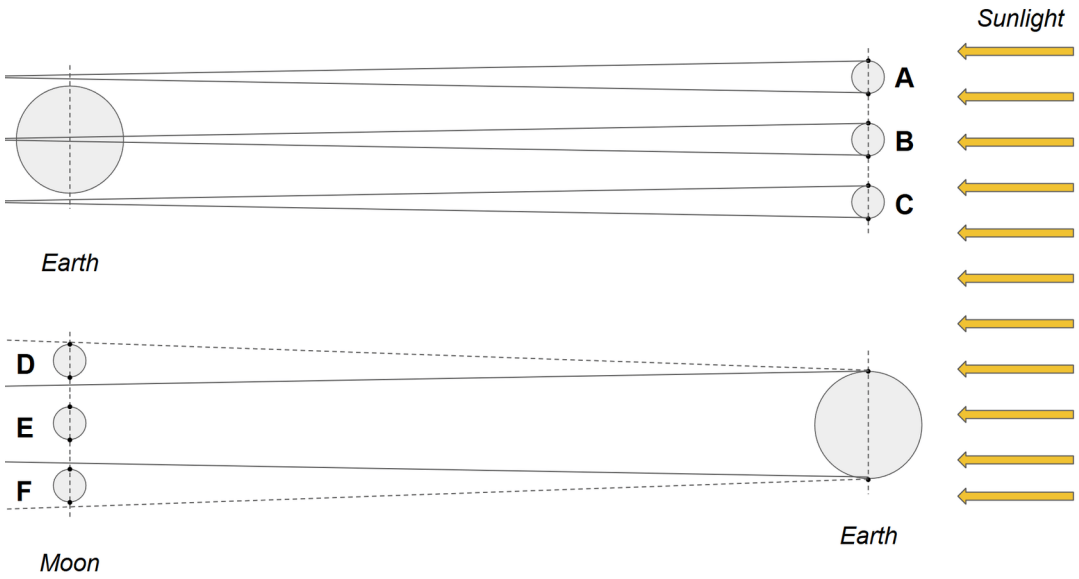
1. *Examine the top model (solar eclipse).*
    1. Which people (A-E) are in the **umbra** and experience the full solar eclipse?
    2. Is the **umbra** a smaller or larger shadow than the basic shadow from 1.7.1?
    3. Which people (A-E) are in the **penumbra** and experience a partial solar eclipse?
    4. Is the **penumbra** a smaller or larger shadow than the basic shadow from 1.7.1?
2. *Examine the bottom model (lunar eclipse).*
    1. Is the moon in the umbra or penumbra in this model? Is there any difference in how many people can see it compared to the model in 1.7.1?

1.7.3 The Moon's Tilted Axis

Model

The orbital axis of the moon is actually tilted with respect to the Earth's orbit around the sun. Depending on where the Earth is in it's orbit, the new moon (responsible for solar eclipses) can be above or below a line from the sun to the Earth.





Two models show the umbral and penumbral shadows from the Earth and Moon with multiple moon positions.

1. Which moon position(s) (A-C) will create a shadow on Earth and result in a solar eclipse?
2. Why won't the other moon position(s) result in a solar eclipse?
3. Which moon position(s) (D-E) will be in the full shadow of the Earth and appear as a total lunar eclipse?
4. Which moon position(s) (D-E) will be in the partial shadow of the Earth and appear as a lesser (penumbral) lunar eclipse?
5. Summarize all the ideas about solar eclipses:
    1. What conditions need to be met in order for a total solar eclipse to occur?
    2. What is this a rare event that not everyone on Earth is able to experience?

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2: ORBITS AND GRAVITATION

2.1: Newtonian Gravitation
2.2: Tides
2.3: Kepler Orbits
2.4: Transfer Orbits
2.5: Newtonian Orbits

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2.1: Newtonian Gravitation

2.1.1 Gravity and No Gravity

Model

A satellite orbits around the Earth on the path shown. On the figure, draw an arrow on the satellite to show the direction it is moving at this snapshot in time.



Satellite orbiting Earth with position marked for analyzing motion under changing gravity.

1. Imagine that at this moment in time, the force of gravity increased. Draw the path the satellite would travel and label the path **"More Gravity."** Explain your thinking. How did you determine this path?
2. Imagine that at this moment in time, the force of gravity decreased. Draw the path the satellite would travel and label the path **"Less Gravity."** Explain your thinking. How did you determine this path?
3. Imagine that at this moment in time, the force of gravity was turned off. Draw the path the satellite would travel and label the path **"No Gravity."** Explain your thinking. How did you determine this path?

Summary

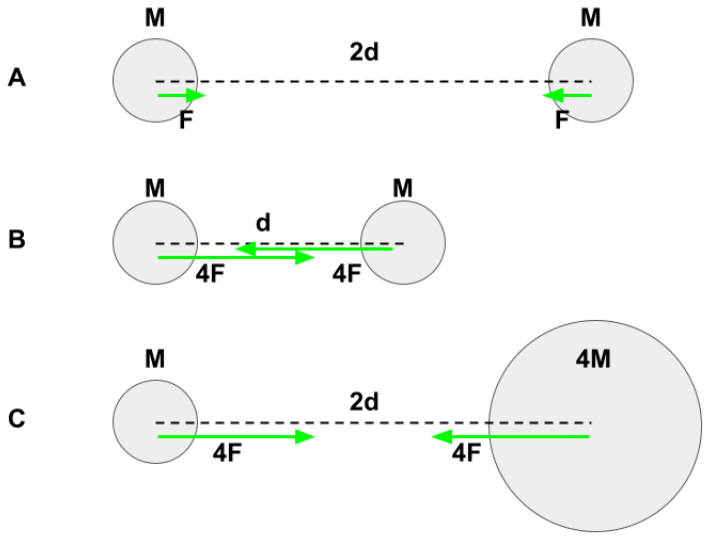
When there are no forces acting on an object in motion, that object will:

Forces cause objects to:

2.1.2 Force of Gravity: Mass and Distance

Model

In the model below, pairs of objects are shown at different distances. The arrows represent the **gravitational force** between the objects. A larger arrow means more force.



Object pairs A, B, and C comparing masses, distances, and gravitational forces.

1. Identify the following comparisons. These do not need to be CER format:
    1. Compare A and B. What changed about the distance between the objects and the masses of the objects? What changed about the force of gravity between the objects?
    2. Compare A and C. What changed about the distance between the objects and the masses of the objects? What changed about the force of gravity between the objects?
    3. For each pair of objects, how does the force experienced by the object on the left compare to the force experienced by the object on the right?
2. Summarize as a CER (you might use your comparisons as evidence): What makes the force of gravity go up? What makes the force of gravity go down?

Summary

Forces are interactions between two objects that push or pull the objects. These forces change the way an object moves. Forces always come in pairs. In any interaction, each object experiences the same force in opposite directions. This equal and opposite relationship is called **Newton's Third Law**.

The strength of the force of gravity is related to the mass of the interacting objects and the distance between the center of mass of those objects. Both objects experience the same force but in opposite directions. The strength of this force is represented by the relationship:

$F_{\text{gravity}} \propto \frac{m_1 \times m_2}{r^2}$

Apply

Rank the following pairs of objects from lowest gravitational force to highest gravitational force. Try putting the values given into the proportional relationship above. You may use a calculator.

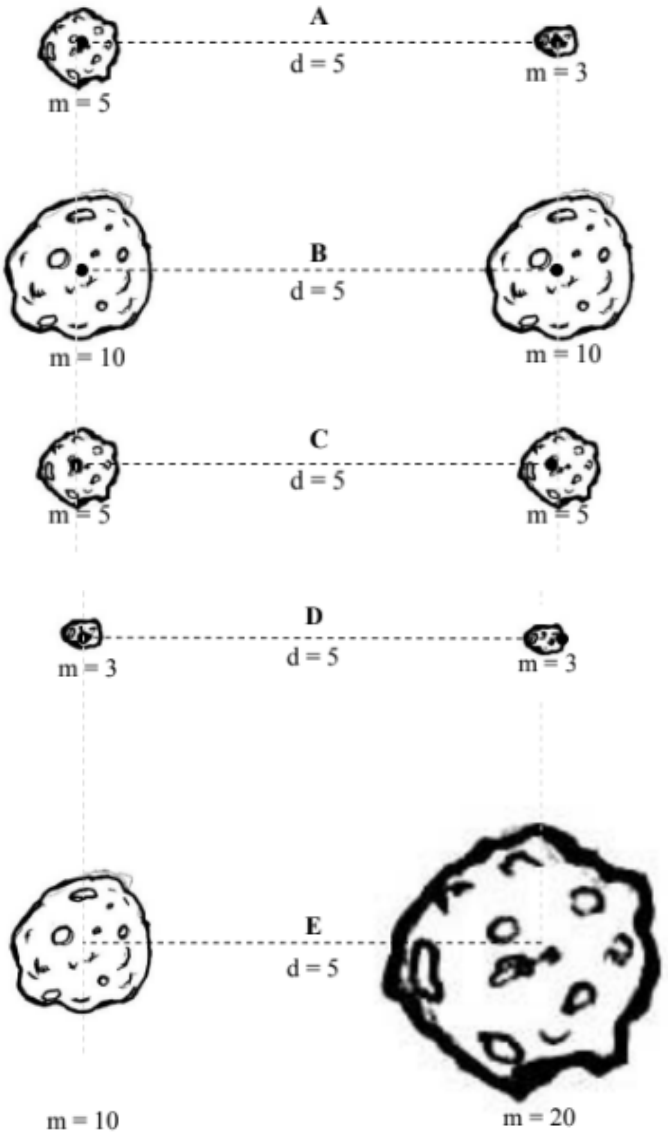
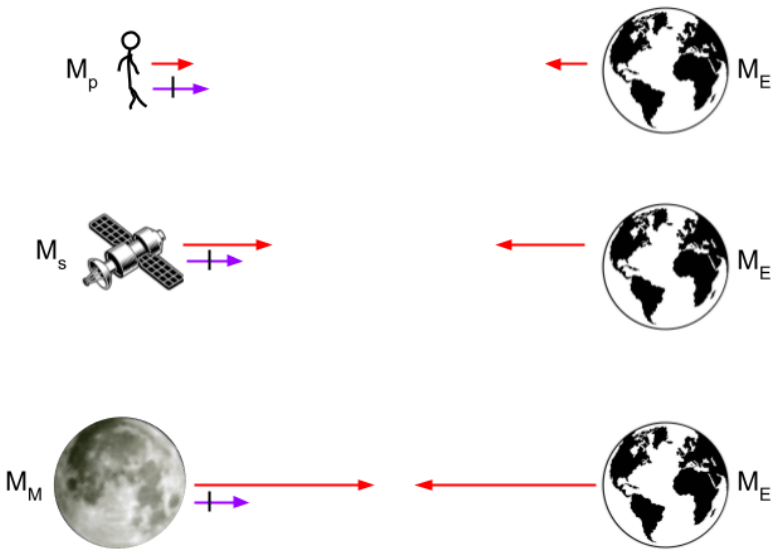


Image Credit: Astronomy Interactives from the Astronomy Education Department at the University of Nebraska-Lincoln (https://astro.unl.edu/interactives/)

2.1.3 Force and Motion

Model

In the model below, the force of gravity and acceleration of gravity are shown for three objects. On each object, the top arrow represents the force of gravity that we just explored. The bottom arrow represents the acceleration of the object, which represents how the motion changes based on the force of gravity.



Earth and three objects showing varying gravity force arrows and equal acceleration arrows.

1. For each Earth–object pair, how does the force of gravity on the object compare to the force of gravity on the Earth?
2. Compare across objects. Rank the forces of gravity that each object experiences.

   Same F for all Objects OR Greatest _____ _____ _____ **Least**

3. Based on your responses, predict how the masses of the three objects (not Earth) compare.

   Same M for all Objects OR Greatest _____ _____ _____ **Least**

4. Compare across objects. Rank the acceleration of gravity that each object experiences.

   Same a for all Objects OR Greatest _____ _____ _____ **Least**

5. Use your responses to make a connection between force, mass, and acceleration. Circle the statement that best matches the patterns you see:

- Mass does not affect acceleration.
- With more mass you need more force to get the same acceleration.
- With more mass you need less force to get the same acceleration.

Summary

The net force (ΣF) acting on an object is equal to the product of the mass of the object and the object's acceleration. This relationship is called **Newton's Second Law**.

$$\Sigma F = ma$$

The net force causes this acceleration. When objects have more mass, they experience less acceleration for the same net force. You can say this another way by rearranging the equation:

$$a = \frac{\Sigma F}{m}$$

To get the same acceleration, you need more force on objects with more mass. For curved motion, acceleration points inward toward the center of the curve.

With gravity, more mass leads to more force, so the mass of the object ends up canceling out. The acceleration is only based on the mass of the other object and the distance between the two objects.

$F_g \propto \frac{m_1 \times m_2}{d^2}$

$a_1 \propto \frac{m_2}{d^2}$

2.1.4 Multiple Forces

Model

In this model, there are three objects that exert gravitational forces on each other.

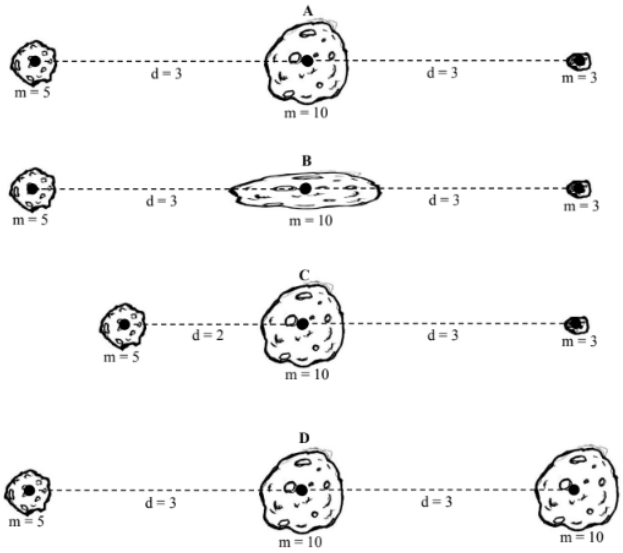


Image Credit: Astronomy Interactives from the Astronomy Education Department at the University of Nebraska-Lincoln (https://astro.unl.edu/interactives/)

1. Draw a force arrow on each middle object. Make the length represent the strength of the force, so if the force to the left is greater than to the right, make the arrow to the left longer than the arrow to the right.
2. Next to each object, write what direction it will change its motion.
3. Next to the objects on the left, draw an arrow to represent the force from both the middle and right-most object. Scale them to show which force is bigger.
4. Next to the objects on the right, draw an arrow to represent the force from both the middle and left-most object. Scale them to show which force is bigger.
5. When an object interacts with two other objects, do you simply add the forces together? If not, explain how you identify the change in motion of an object when there is more than one force acting on that object.

Summary

Forces have _____ and _____. When adding two or more forces together, you need to take both into account.

The change in motion of the object is based on the _____ force acting on that object.

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2.2: Tides

Tides from the Earth–Moon System

Recall the relationships we found for the force of gravity and the acceleration due to gravity:

$F_g \propto \frac{m_1 \times m_2}{d^2}$

$a_1 \propto \frac{m_2}{d^2}$

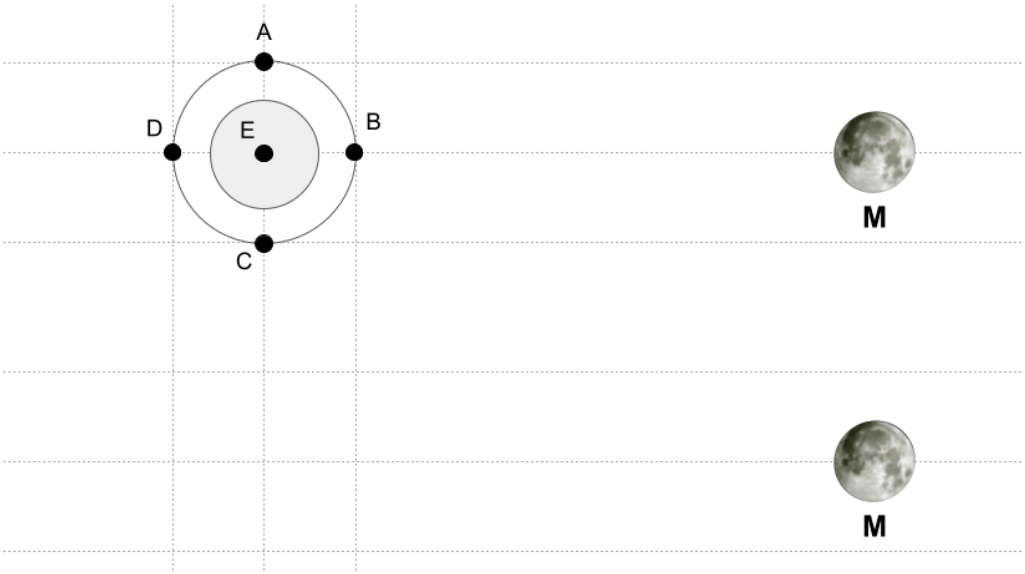
In this activity, we will focus on the effect of gravity, which means focusing on acceleration. Use this proportionality to determine relative amounts of motion in this activity:

$a_1 \propto \frac{m_2}{d^2}$

2.2.1 The Gravitational Pull of the Moon

Model

The Earth is shown as a gray circle below. The ring around the Earth represents the ocean. The diagram is not to scale. The Moon exerts a gravitational force on both the Earth and its oceans.



Earth and surrounding ocean ring with labeled points showing Moon's gravitational effect.

1. Compare the mass of the Moon for all lettered points.

   Same M for all Points OR Greatest _____ _____ _____ **Least**

2. Compare the distance between the Moon and each of the lettered points.

   Same d for all Points OR Greatest _____ _____ _____ **Least**

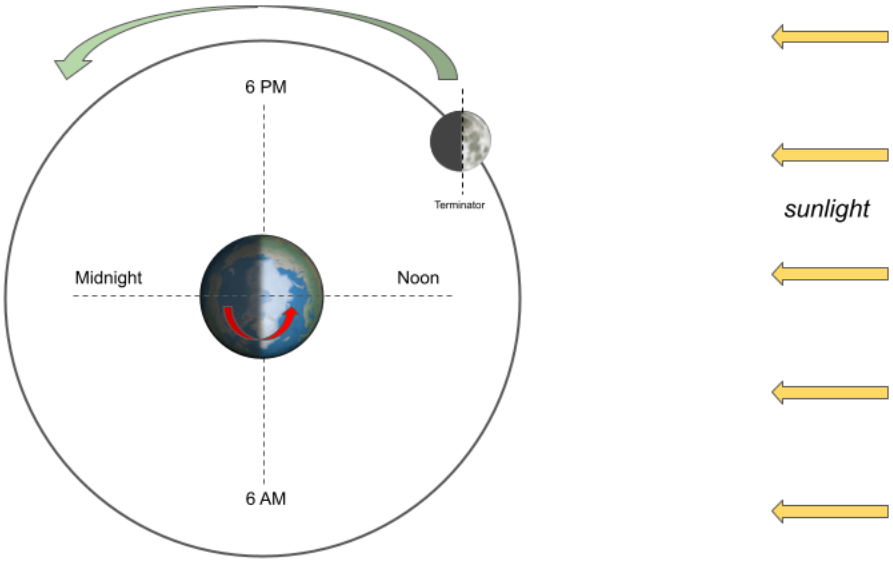
3. How should the acceleration (g) compare for each of the lettered points?

Same a for all Points OR Greatest _____ _____ _____ **Least**

4. Based on your responses, construct a new model below the first that shows how the Earth and oceans respond to the Moon's gravitational pull:
   - Draw arrows on each point to show the direction of the acceleration. Make the size of the arrows match what you said in the previous question.
   - On the lines below the original image, shift the points based on the length and direction of the arrows. They might not all shift the same amount.
   - Draw a new Earth circle centered around the E dot. Be sure to draw it the same size as the model above.
   - Use curved lines to connect dots A–D to make a new circle/oval. This represents the surface of the oceans.
5. Examine the sea level compared to the Earth. Label portions of the Earth **High Tide** and **Low Tide**.
6. Summarize: Where on Earth do high tides occur?

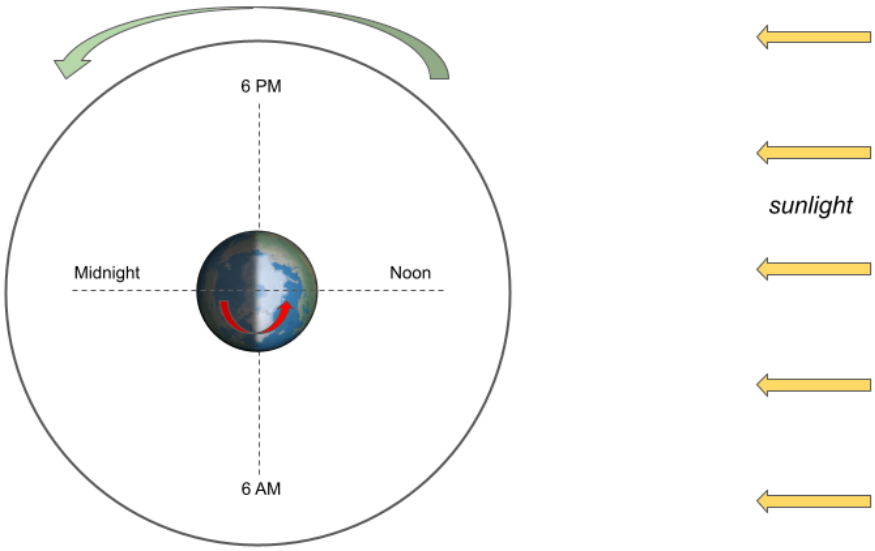
2.2.2 Tide Schedule

Model



Earth–Moon–Sun system used to model high tides, low tides, and tidal timing.

1. Draw in the ocean to show what you learned about high and low tides, based on the position of the Moon.
2. Label the time(s) of day that correspond to high tide.
3. For the Earth on the diagram below, there is a high tide that occurs at 9 PM.
   - Draw in the ocean to show high and low tides.
   - Draw the position of the Moon to make this occur.
   - Draw the phase of the Moon when it is in this position.



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2.3: Kepler Orbits

2.3.1 Exploring Orbits

Model

Go to the simulation: https://tinyurl.com/mysolarsystemPHET

Make adjustments and click the options to show the velocity and force. Before running the simulation, always click the button to **"Follow Center of Mass"**.

Pay attention to:

- Orbital Shape
- Orbital Velocity (Green Arrow)
- Gravitational Force (Purple Arrow)
- Orbital Period

Complete the table to record what you observe:

Exploring Orbits Observations

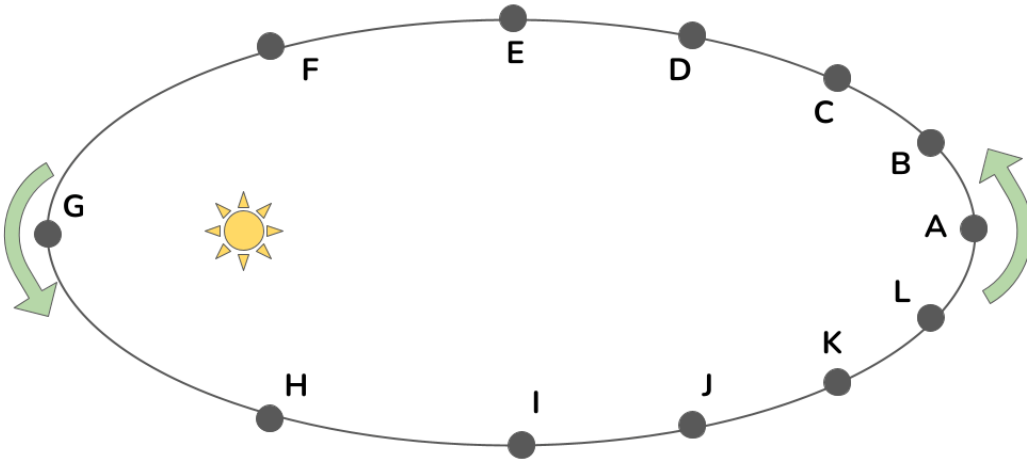
We Will Change...	We Predict...	We Observed...

1. **Summarize:** Construct one or more CERs to identify patterns or summarize what determines the orbits of a two-body system.

2.3.2 Kepler Orbits

Model

The model below shows a planet at different positions in it's orbit around a star. The same amount of time elapses between successive letters (A to B, B to C, etc.).

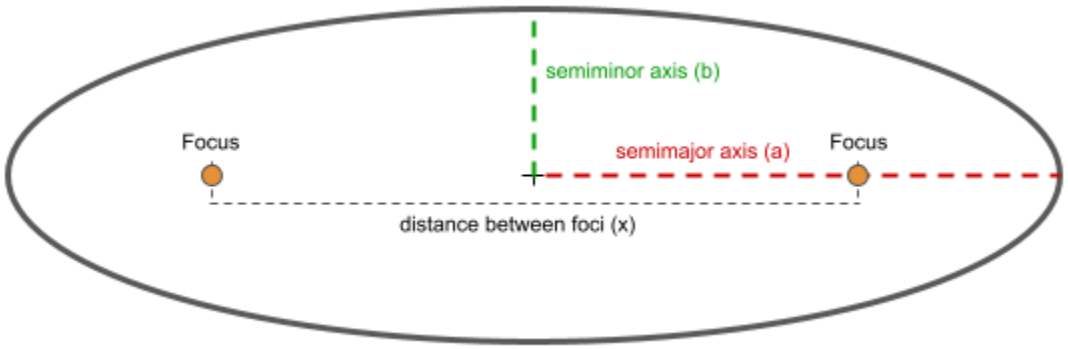


Adapted from Lecture-Tutorials for Introductory Astronomy, Second Edition

Planet orbit with labeled positions showing changing orbital speed around a star.

1. Does the planet appear to travel the same distance each month?
2. At which positions is the planet moving the fastest? The slowest? Explain.
3. At position D, is the speed of the planet increasing or decreasing? Explain.
4. Draw a line between each lettered position of the planet and the center of the star. Describe how the wedges that form between planet positions compare.
5. Create a concise statement that describes the relationship between a planet's orbital speed and its distance from its companion star.

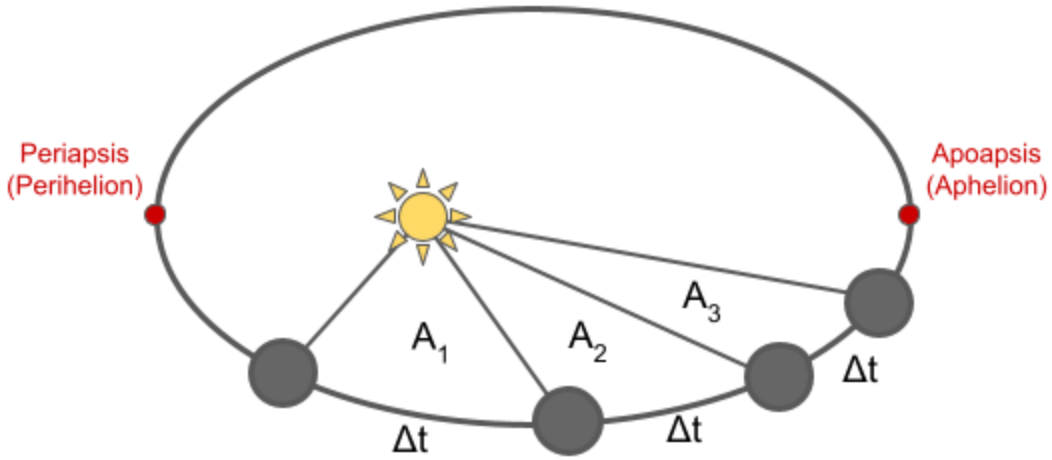
Summary



eccentricity

$$e = \frac{x}{2a}$$

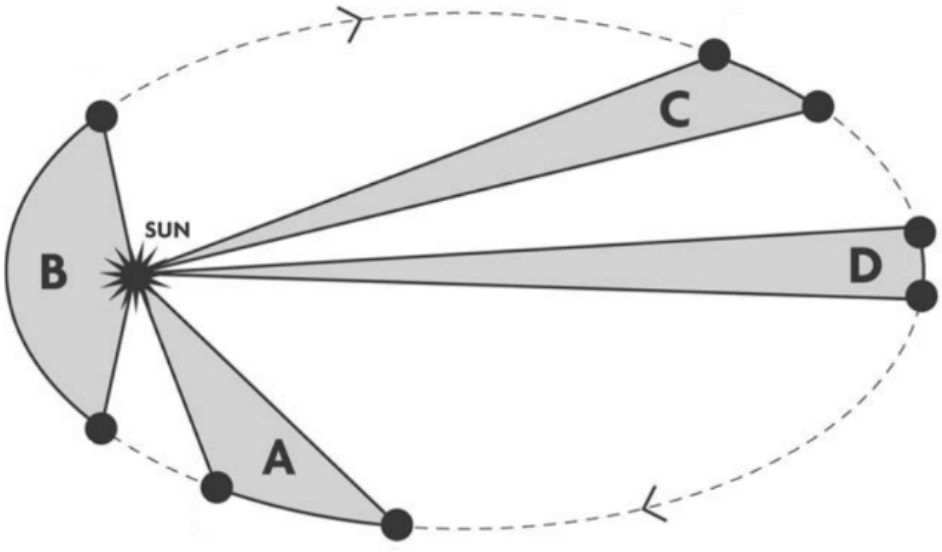
Kepler's First Law states that the orbital path of planets trace out an **ellipse** which has two foci. The start (or other parent body) is at one focus and the other focus is empty. The **eccentricity** of the ellipse is the distance between each focus divided by twice the semimajor axis. A circle has an eccentricity of zero.



As objects travel in their orbit, they trace out **Equal Area** wedges in **Equal Amounts of Time**. This relationship is known as **Kepler's Second Law.**

2.3.3 Arcs and Areas in an Orbit

Model



Elliptical orbit divided into wedges showing orbital arcs and equal-area sectors.

Image Credit: Astronomy Interactives from the Astronomy Education Department at the University of Nebraska-Lincoln (https://astro.unl.edu/interactives/)

Information Processing

1. Identify some evidence (No CER needed)
    1. Which wedge is the widest (biggest angle)? Is the planet close or far from the star in that portion?
    2. Which wedge is the narrowest (smallest angle)? Is the planet close or far from the star in that portion?

3. How do the areas of each wedge (approximately) compare?

Critical Thinking: Write a CER response:

1. How do you think the length of time it takes for the planet to traverse the arc of each wedge compares?

2.3.4 Orbital Period

Model

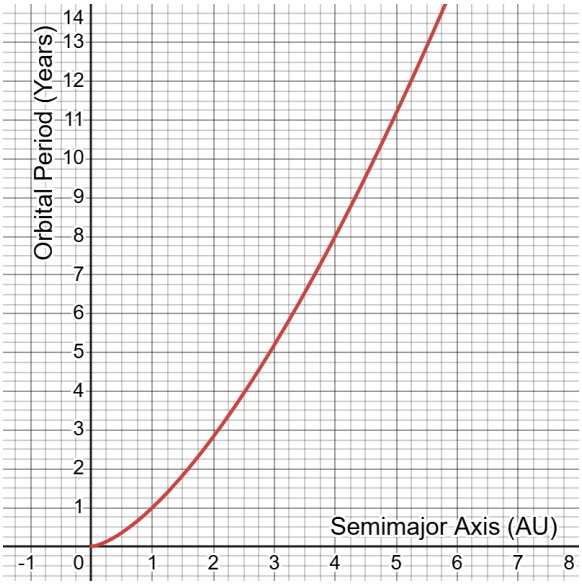
In a **Planetarium** or using planetarium software (eg, World Wide Telescope), view the orbits of planets in our solar system. All planets orbit the same object (the Sun) but their orbits are different.

1. What planet is traveling the fastest? Is it close or far from the Sun?
2. What planet is traveling the slowest? Is it close or far from the Sun?
3. What planet takes the most time to complete an orbit (Period)? Is it close or far from the Sun?
4. What planet takes the least time to complete an orbit (Period)? Is it close or far from the Sun?

2.3.5 Kepler Law 3

Model

This graph shows how the orbital period (time to complete one orbit) of an object in our solar system varies with distance. An AU is an Astronomical Unit and is equal to the average distance between the Earth and the Sun. This graph was created using Desmos.



1. When satellites are closer to the object they orbit, is the orbital period longer or shorter?
2. If I double the size of the orbit (orbital distance), does the orbital period double? If not, is it more than double or less than double? Cite examples from the graph.

Summary

The relationship between the orbital distance and orbital period is given by the equation:

$P^2 \propto a^3$

This equation is known as **Kepler's 3rd Law**. The symbol $\propto$ means "proportional to" and shows a general trend relationship. The exact equation was determined later by Isaac Newton.

Kepler's third law becomes an equality when used for objects in our solar system if the period is measured in years and the semimajor axis is measured in Earth–Sun distances, which are called Astronomical Units (AU).

Apply

The table below provides a partial list of the orbital periods (in years) and orbital distances (in AU) for six planets orbiting a one solar-mass star. The mass of each planet is also provided (in Earth masses). Rank the orbital periods of the planets. It might help to determine some of the unknown values.

Activity Credit: Astronomy Interactives from the Astronomy Education Department at the University of Nebraska-Lincoln (https://astro.unl.edu/interactives/)

Planet	Orbital Distance (AU)	Orbital Period (Years)	Mass (Earth Masses)
A		20	500
B	0.8		375
C	3.0		100
D		2.0	50
E	5.0		3
F		3.5	0.5

2.3.6 Orbital Speed

Model

The equations below identify an approximate average speed by using Kepler's Third Law ($P^2 = a^3$) and assuming a circular orbit. They originate by taking the circumference of that orbit ($2\pi a$) and dividing by the time (period, P).

These equations are only valid for objects orbiting a solar-mass star and the units are in Astronomical Units per Year (AU/year).

$v_{avg} = \frac{2\pi a}{P}$

$v_{avg} = \frac{2\pi}{P^{1/3}}$

$v_{avg} = \frac{2\pi}{a^{1/2}}$

1. Use the equations, along with Kepler's 3rd Law, to complete this table for the planets in our solar system.

Orbital Speed Table

Planet	Orbital Distance	Orbital Period	Orbital Speed
Mercury	0.4 AU		
Venus	0.1 AU		
Earth	1.0 AU		
Mars	1.5 AU		

Planet	Orbital Distance	Orbital Period	Orbital Speed
Jupiter	5.2 AU		
Saturn	9.6 AU		
Uranus	19.2 AU		
Neptune	30 AU		

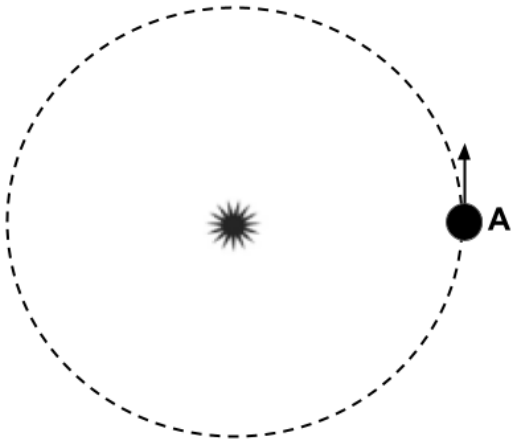
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2.4: Transfer Orbits

2.4.1 Speeding Up

Model

Observe the simulation at https://tinyurl.com/mysolarsystemPHET to see how changing the speed of an orbiting object changes the orbit itself. An object makes a circular orbit around a star. At point A, the speed of the object increases from that circular orbit speed.

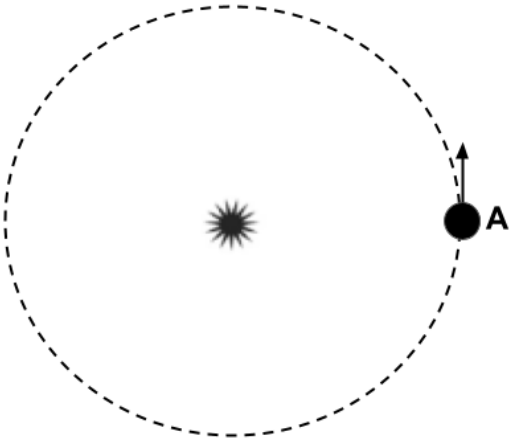


1. Draw out the new orbit as a dashed line.
2. Put a dot at the point on the orbit that is directly on the other side of the star as Point A. Label it B.
3. Is Point B a periapsis or apoapsis? Is the object moving faster or slower at Point B than at Point A?
4. Does increasing the speed of an object in circular orbit push the other side of the orbit further from the star or does it pull the other side of the orbit closer in to the star?

2.4.2 Slowing Down

Model

Observe the simulation at https://tinyurl.com/mysolarsystemPHET to see how changing the speed of an orbiting object changes the orbit itself. An object makes a circular orbit around a star. At point A, the speed of the object decreases from that circular orbit speed.

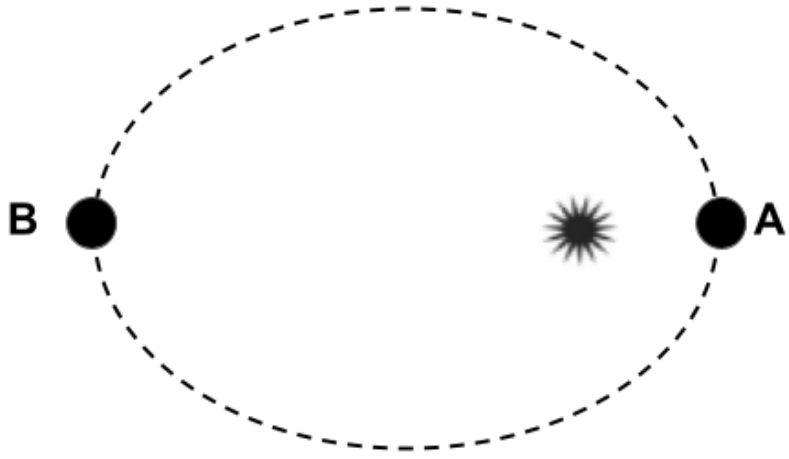


1. Draw out the new orbit as a dashed line.
2. Put a dot at the point on the orbit that is directly on the other side of the star as Point A. Label it C.
3. Is Point C a periapsis or apoapsis? Is the object moving faster or slower at Point C than at Point A?
4. Does increasing the speed of an object in circular orbit push the other side of the orbit further from the star or does it pull the other side of the orbit closer in to the star?

2.4.3 Adjusting to Circular Orbits from Elliptical Orbits

Model

The model below shows an elliptical orbit of a satellite around a star. Points A and B are the periapsis and apoapsis of the orbit.

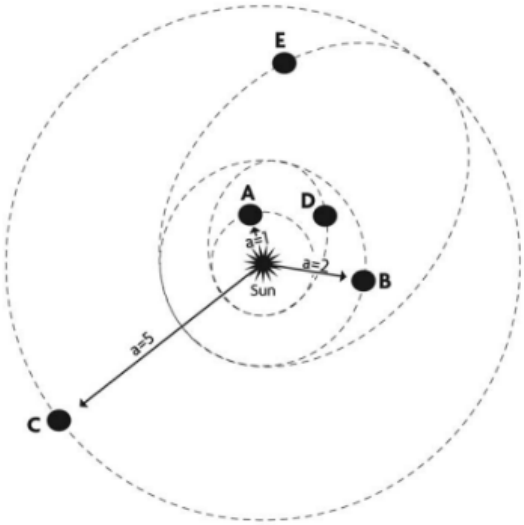


1. Is the planet moving faster at point A or B? Explain how you know.
2. In order to turn the orbit into a circular orbit that includes point A, should the satellite speed up or slow down at point A? Explain your reasoning.
3. In order to turn the orbit into a circular orbit that includes point B, should the satellite speed up or slow down at point A? Explain your reasoning.

4. What should be at the center of both circular orbits?
5. Draw both circular orbits.

2.4.4 Many Orbits

Model



Multiple circular orbits A–E around a star used to compare orbital speeds.

Image Credit: Astronomy Interactives from the Astronomy Education Department at the University of Nebraska-Lincoln (https://astro.unl.edu/interactives/)

1. Which orbit (A–E) is the fastest? How do you know?
2. Which orbit (A–E) is the slowest? How do you know?
3. Describe the process (speeding up / slowing down) to get from circular orbit A to circular orbit B.
4. Describe the process (speeding up / slowing down) to get from circular orbit C to circular orbit B.
5. In general, what is the process to change the size of a circular orbit?

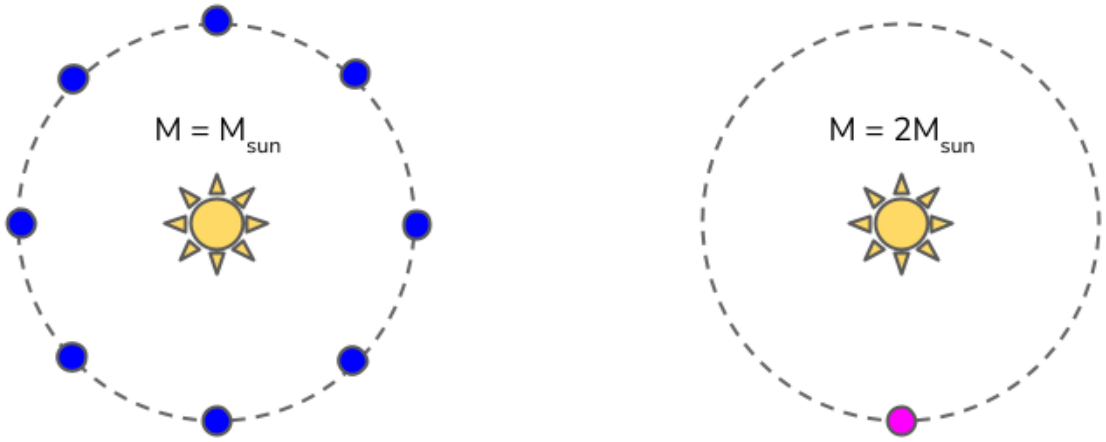
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2.5: Newtonian Orbits

2.5.1 Circular Orbital Speed

Model

This model shows two gravitational orbits of an object around a star. The stars have different masses, as shown. Assume the orbiting object is the same object in both systems.



Two different star–planet orbit systems with different star masses for comparing orbital speed.

1. Which orbiting system (left or right) will have a stronger force of gravity? Explain your reasoning.
2. Which orbiting system (left or right) do you think will have a faster moving planet? Explain your reasoning.
3. Based on your response above, draw additional dots for the system on the right around the orbit. Assume the same amount of time between dots as the model on the left, so decide if they should be further apart or closer together. Explain your reasoning.

Summary

The speed of a circular orbit does not depend on the mass of the orbiting object (for example, a planet). It depends on the mass of the object being orbited (for example, a star) and the distance between the planet and the star.

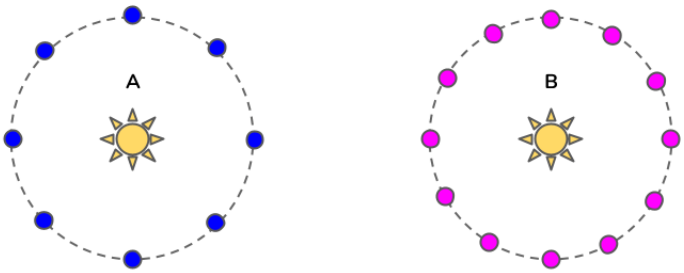
It is based on the strength of gravity and follows the relationship:

$$v_{\text{circular orbit}} \propto \sqrt{\frac{M}{r}}$$

2.5.2 Weighing a Star

Model

The model below shows two orbits of planets around different stars. Assume the same amount of time elapses between each dot in the orbit.



Two planetary orbits with equal time markers used to compare star masses.

1. Which orbit has a faster moving planet? Explain how “speed” can be determined on these dot models of an orbit.
2. Which orbit must have a more massive star? Explain your reasoning.
3. Explain how we can use measurements of a satellite orbit to determine (or at least compare) the mass of the central body that satellite orbits.

Summary

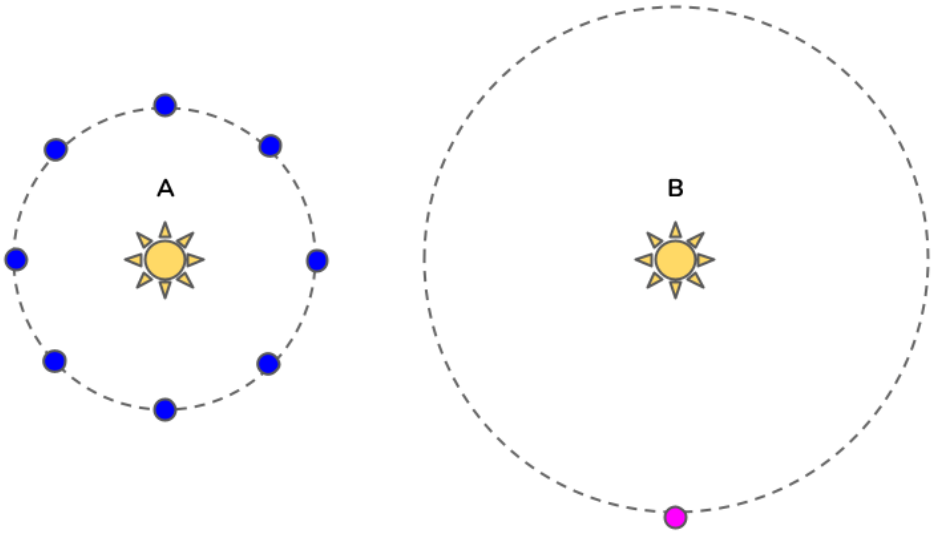
We can rearrange the same equation from earlier to show that the mass of the central body can be determined by the relationship:

$M_{\text{central body}} \propto v^2 r$

2.5.3 Speed on an Orbit

Model

In the model below, the speed of the satellite is the same for both objects.



Two satellite orbits of different sizes with equal orbital speed for comparison.

1. Which orbit (A or B) is a bigger path?
2. If the satellites travel at the same speed, how will the length of time needed for each satellite to complete one orbit compare?
3. If we put dots at equal intervals of time, which orbit will have more dots? Explain your reasoning.
4. Draw the dots to show the orbit for the satellite on the right. Make sure they represent the same amount of time between dots as the orbit on the left.

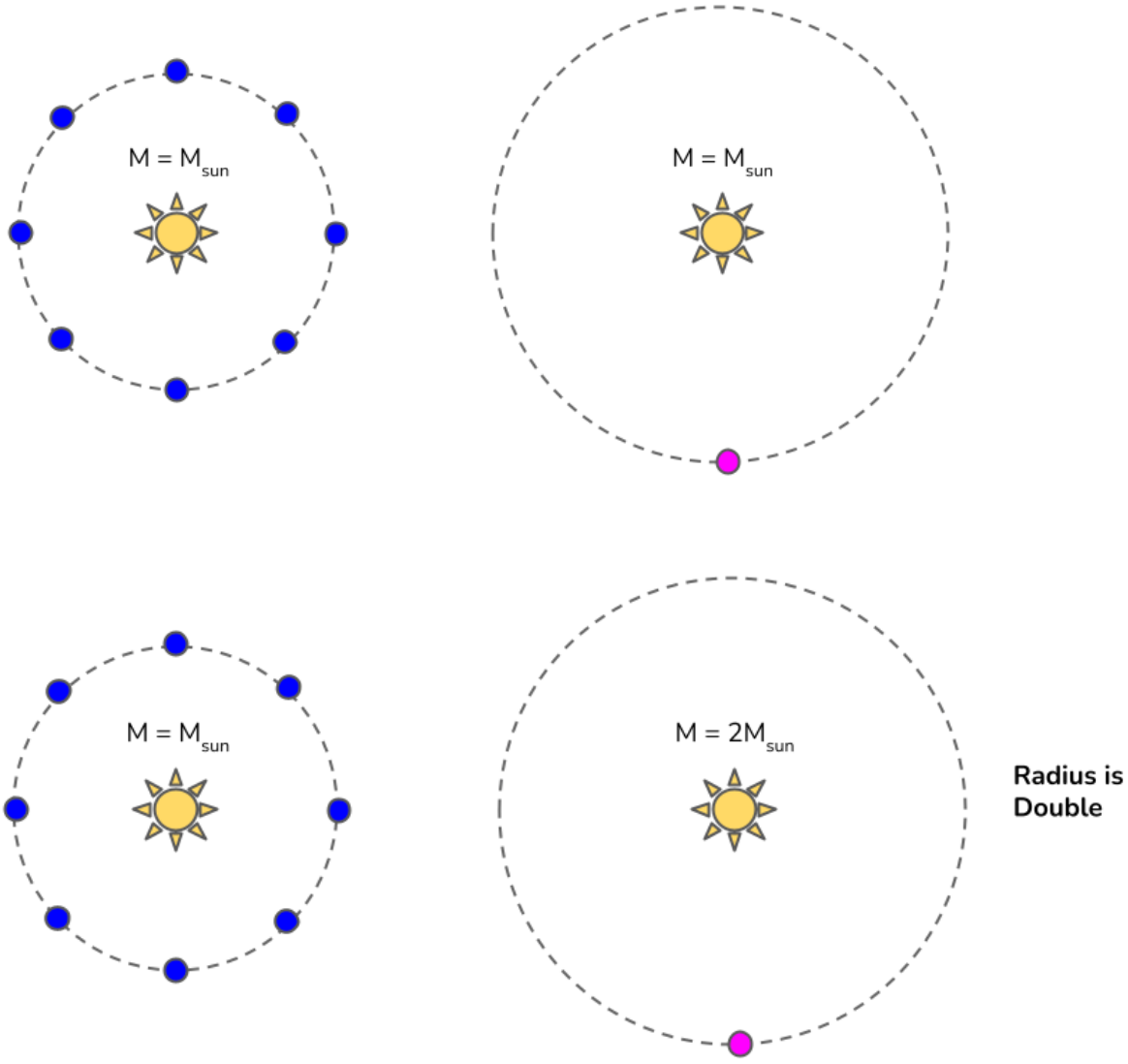
Summary

The speed of the orbiting satellite is represented in this model by the spacing between the dots.

Apply

Use the orbit on the left to complete the model for the orbit on the right, based on the values given for M and r.

Explain your reasoning for each model based on how the speed of each satellite should compare. Then identify which orbit takes longer to complete.



Summary

The time it takes for a satellite to complete one orbit is called the **orbital period**.

It depends on the radius of the orbit and the mass of the central body and is related by the equation:

$$P_{\text{satellite}} \propto \sqrt{\frac{r^3}{M_{\text{central body}}+m_{\text{satellite}}}}$$

We will not use this equation much, but the powers in the equation show that the period increases with radius and decreases with mass.

The radius plays a bigger role than mass because it is raised to the third power.

This equation can be thought of as:

$$P_{\text{satellite}} \propto \sqrt{\frac{\text{radius}\times\text{radius}\times\text{radius}}{M_{\text{central body}}+m_{\text{satellite}}}}$$

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3: LIGHT AND ASTRONOMICAL MEASUREMENTS

3.1: Determining Speed with the Doppler Method

3.2: Electromagnetic (EM) Radiation

3.3: Measuring Light

3.4: Luminosity Plots

3.5: Spectroscopy

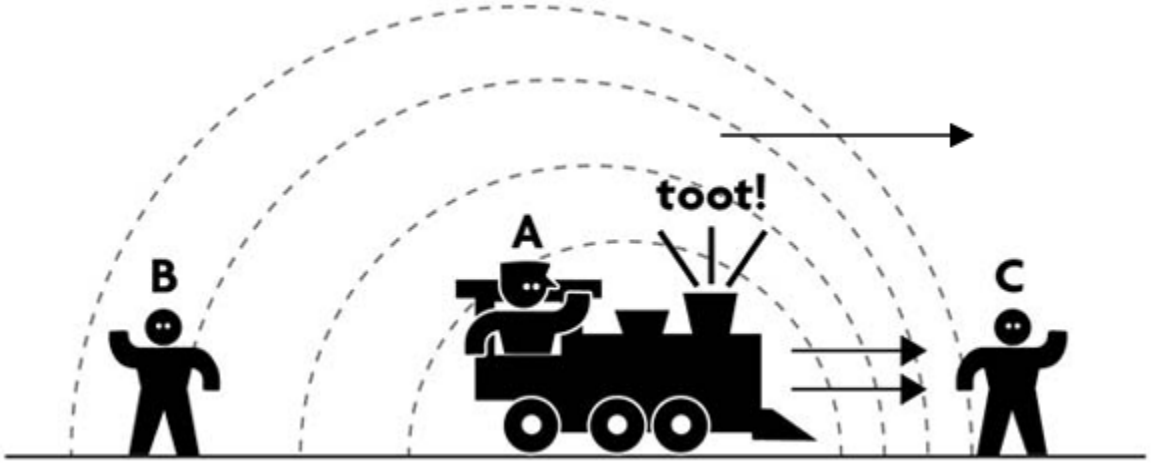
3.6: Applications of Spectroscopy

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3.1: Determining Speed with the Doppler Method

3.4.1 Doppler Shift

Model



1. Which person (A, B, or C) is moving with the source of the sound?
2. Is the source of sound moving towards or away from person B? Is the wavelength of the waves bigger or smaller for that person?
3. Is the source of sound moving towards or away from person C? Is the wavelength of the waves bigger or smaller for that person?
4. Rank the wavelength of the waves that each person experiences from smallest to greatest.

Summary

When an object is moving towards you the wavelength is shifted to be _____ and the frequency is shifted to be _____.

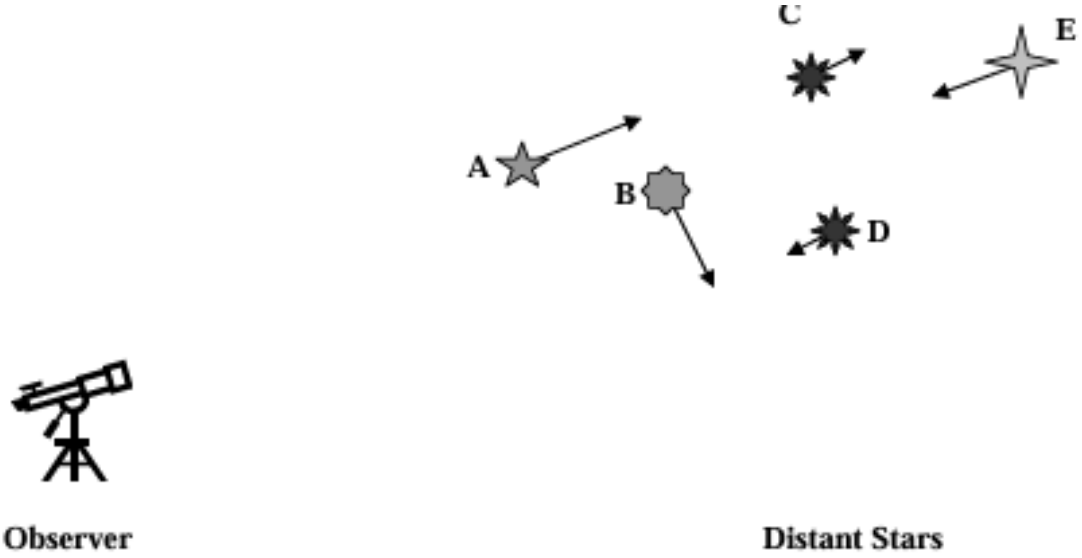
When an object is moving away from you the wavelength is shifted to be _____ and the frequency is shifted to be _____.

For light, shorter wavelengths mean bluer light and longer wavelengths mean redder light. We can then say the light is **blueshifted** or **redshifted**.

3.4.2 Predicting Shifted Light

Model

An observer looks at 5 stars with relative motion shown by their arrows.

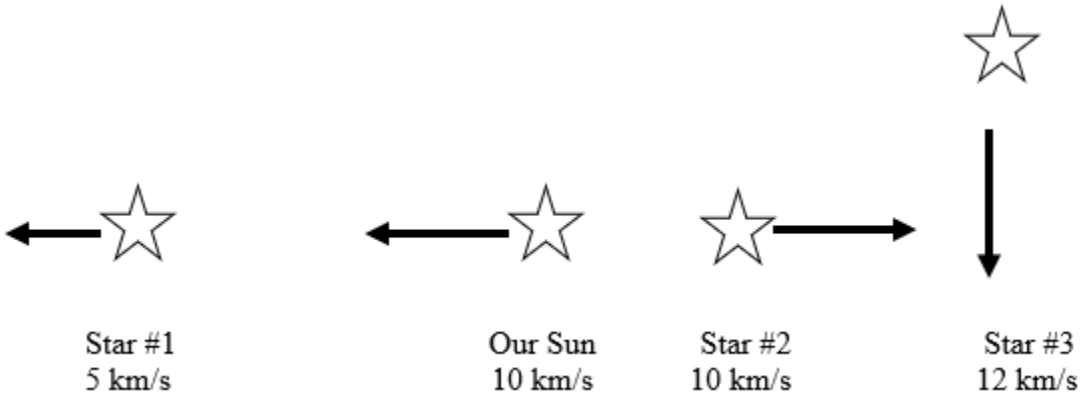


1. Which objects are moving towards the observer?
2. Which objects are moving away from the observer?
3. Are any objects not moving towards or away (even if they are moving)? If so, identify them and explain your thinking.
4. Label each letter as **redshifted**, **blueshifted**, or **no shift** based on the motion and the patterns we discovered earlier. Explain how you determined these labels here.

3.4.3 Determining Relative Speed

Model

We move with our sun and do not notice our own motion. Consider relative velocity as **towards you** if you get closer to that object over time and **away from you** if you get farther from that object over time.



1. Which star(s) ended up closer to our Sun than they started?
2. Which stars ended up farther away from our Sun than they started?
3. Use your responses to come up with a definition of **relative velocity**.
4. Using your definition, identify if the relative velocity of each star is towards or away from us.
5. Based on the relative velocity of each star, label each star as **redshifted**, **blueshifted**, or **no shift** based on the motion and the patterns we discovered earlier. Explain how you determined these labels here.

Summary

The relative velocity of a star is based on how it moves relative to us. We can simply subtract our velocity from the velocity towards

or away from us for each star to figure out the relative velocity, but we have to do so using vectors, which can make the calculation more challenging when we have a two-dimensional problem like this.

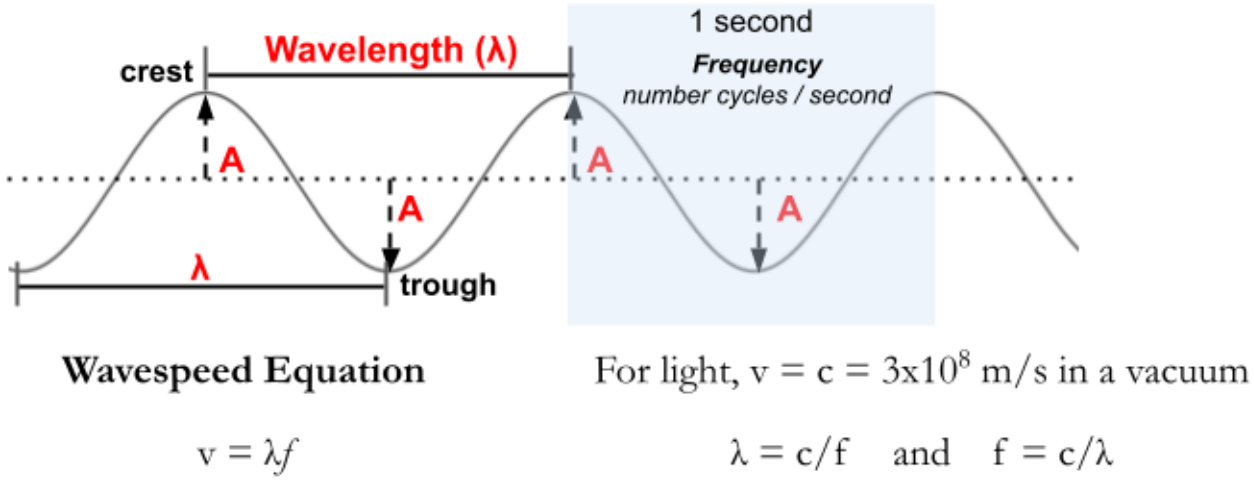
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3.2: Electromagnetic (EM) Radiation

1. Electromagnetic Radiation

1.1 Wavelength Model

Model



Wave diagram showing wavelength, amplitude, and frequency for comparing wave properties.

1. What is the difference between wavelength (λ) and amplitude (A)?
2. How would a wave look if it had a higher frequency?
3. Two waves are traveling at the same speed, but one has a higher frequency. Will it have a longer or shorter wavelength? Explain your reasoning and then draw both waves.

Student Drawing Area

1.2 Colors of Light

Model

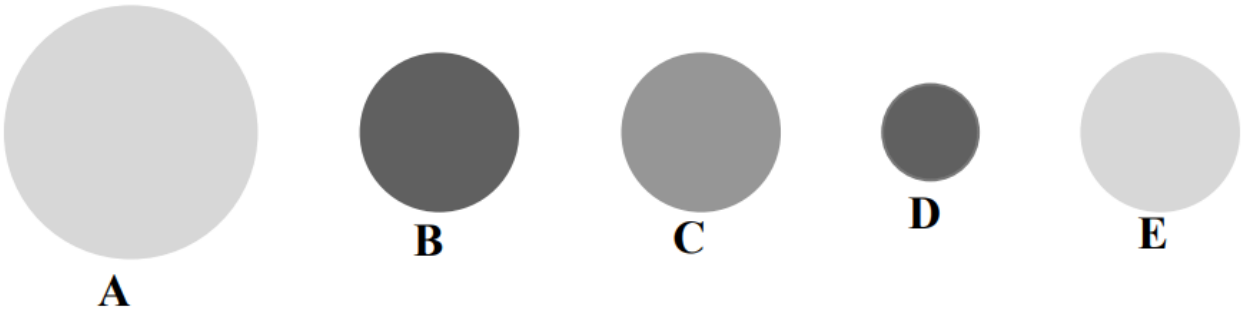
Image needed here with Alt Text: Visible light spectrum showing colors arranged by wavelength and frequency.

1. What is different about the different colors of light?
2. Compare violet (purple) light and red light: Which has a longer wavelength and which has a shorter wavelength?
3. If violet and red light travel past you at the same speed, which color will have more crests pass by you in a given amount of time (frequency)?
4. Identify a pattern: For light, when wavelength increases, frequency:

1.3 Blackbody Radiation

Model

The model below shows different size hotplates. The hotplates that are a lighter color are hotter. Imagine you place a pot with the same amount of water on each burner and heat it up until it boils.



Hotplates of different sizes and temperatures used to compare heating and luminosity.

Image Credit: Astronomy Interactives from the Astronomy Education Department at the University of Nebraska-Lincoln (https://astro.unl.edu/interactives/)

1. Which burner will boil the water fastest? Explain your reasoning.
2. Which burner will boil the water slowest? Explain your reasoning.
3. If two burners are the same size, what determines which burner will boil a pot of water faster? Explain your reasoning.
4. If two burners are the same temperature, what determines which burner will boil a pot of water faster? Explain your reasoning.
5. If you use two burners of different sizes, can you assume that the burner that boils water faster is at a higher temperature? Explain your reasoning.

Summary

Luminosity is based on temperature and size. Overall luminosity follows the pattern:

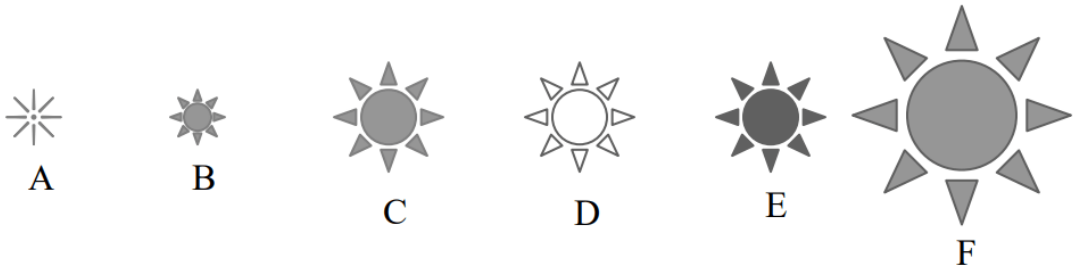
$L \propto AT^4$

This is equivalent to:

$L \propto A \times T \times T \times T \times T$

Apply

1. Compare the luminosity of the stars shown below. Explain your reasoning.



Star	A	B	C	D	E	F
Surface Area	1	1	2	2	2	4
Temperature	1000 K	2000 K	2000 K	3000 K	1000 K	2000 K

Stars of different sizes and temperatures used to compare luminosity.

Image Credit: Astronomy Interactives from the Astronomy Education Department at the University of Nebraska-Lincoln (https://astro.unl.edu/interactives/)

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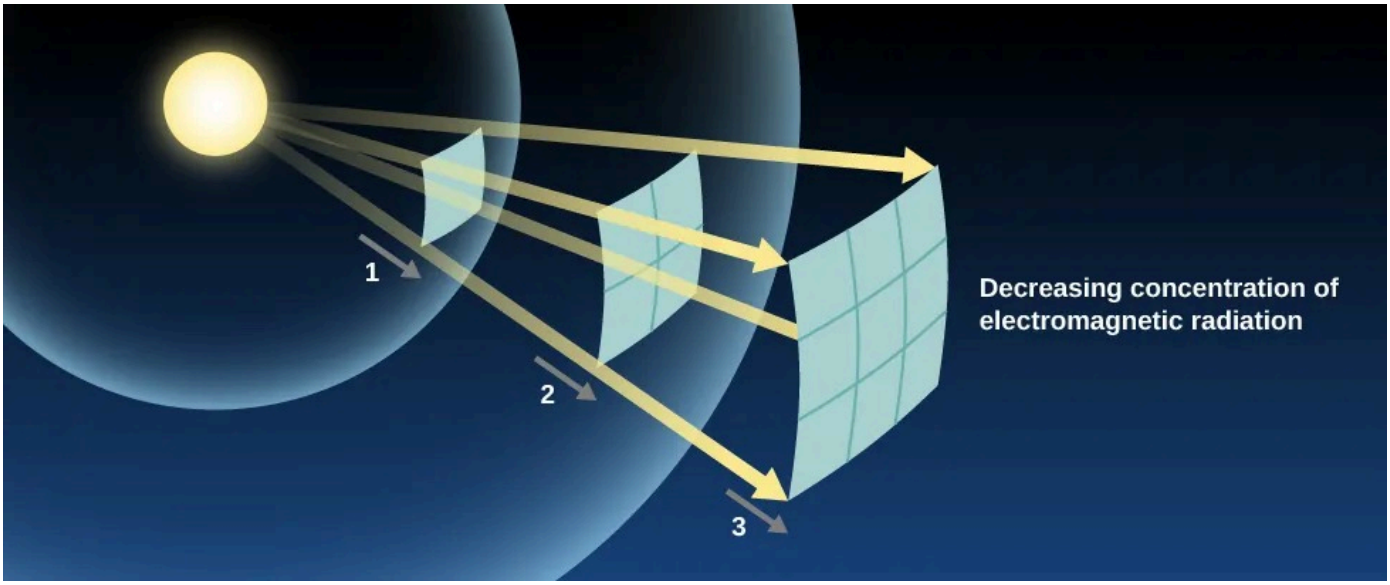
3.3: Measuring Light

1. Measuring Light

1.1 Inverse Square Law of Light

Model

The model below shows how light spreads out with distance. Each **single grid square** is the same size.



Light source illuminating expanding square regions at increasing distances from the source.

Image Credit: OpenStax Astronomy 2e (https://openstax.org/details/books/astronomy-2e)

1. Identify answers to the following:
    1. How should the total amount of light that is spread across the full square at each letter compare?
    2. As distance from the source increases, does this light spread over a smaller or larger area?
2. Construct a CER: How should the amount of light that is spread across **a single grid square** at each distance?
3. The amount of light in a single grid square is the **brightness / intensity of light**. As you get farther from a source, does that brightness / intensity increase or decrease? Explain your reasoning.

Summary

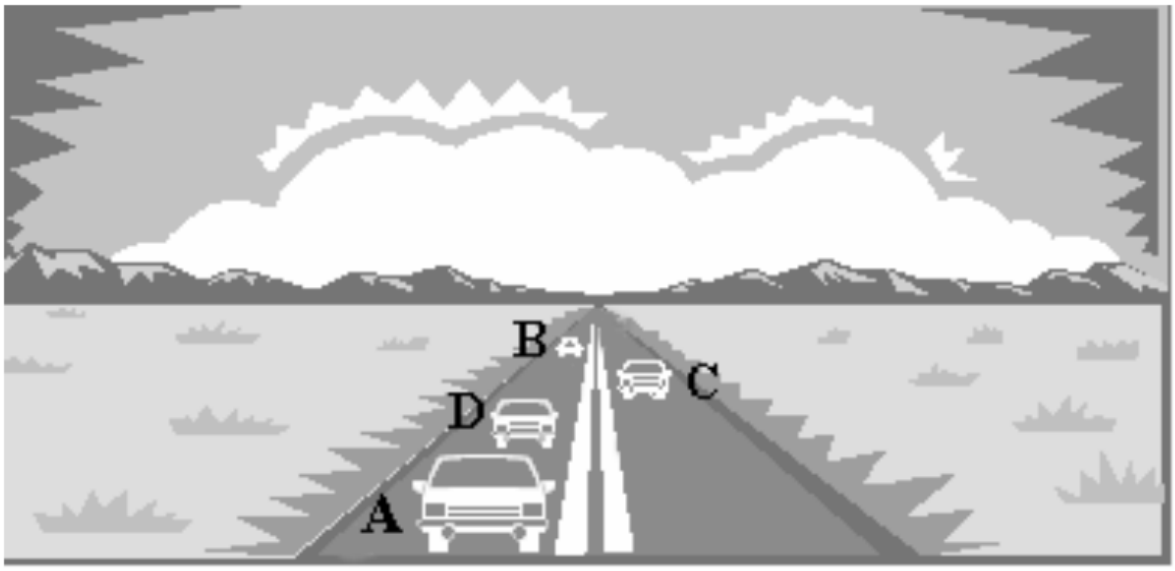
As you get farther from a light source, the brightness / intensity of the light:

Doubling the distance results in _____ of the brightness / intensity. This is called the _____.

1.2 Absolute and Relative Brightness

Model

On the road you see a number of identical cars with their headlights on.



Identical cars with headlights at different distances demonstrating apparent brightness.

Image Credit: Astronomy Interactives from the Astronomy Education Department at the University of Nebraska-Lincoln (https://astro.unl.edu/interactives/)

1. How do you think the amount of light given off by the headlights (Luminosity) compares for the different cars? Explain.
2. How do you think the brightness / intensity of the light as interpreted by your eye compares for the different cars? Explain.
3. If the road is really dark and you cannot see which car is farther and which car is closer, how could you figure out which car is farthest away?

Summary

Relative Magnitude refers to:

Absolute Magnitude refers to:

Absolute Magnitude is a standardization tool to compare stars regardless of their distance. The absolute magnitude of a star is its apparent magnitude when it is a distance of 10 parsecs away.

1.3 Measuring Distance Using Brightness

Model

The image below shows the apparent brightness of 5 stars from Earth. The darker shades represent dimmer stars.



Image Credit: Astronomy Interactives from the Astronomy Education Department at the University of Nebraska-Lincoln (https://astro.unl.edu/interactives/)

The image below shows the absolute magnitude (luminosity) of the different stars. Lower numbers (including more negative values) mean greater luminosity.

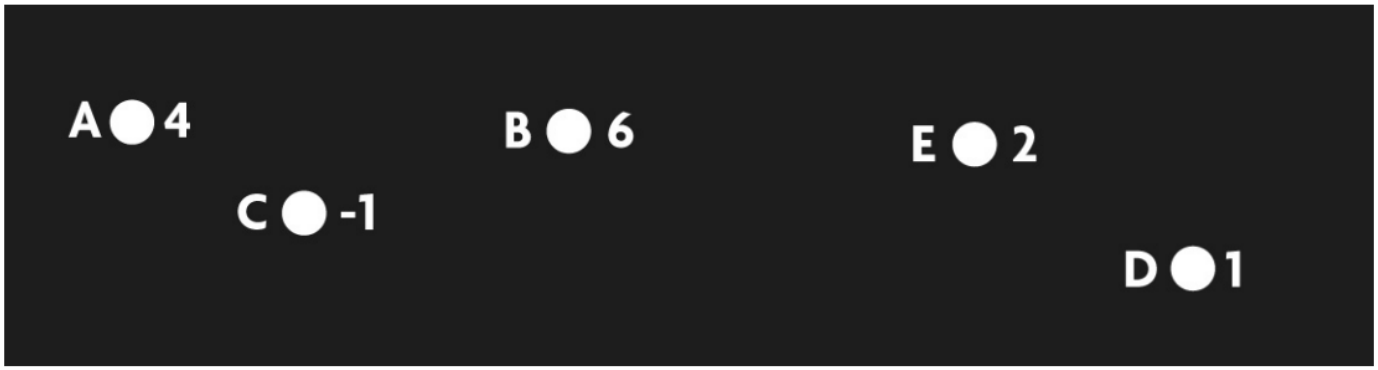


Image Credit: Astronomy Interactives from the Astronomy Education Department at the University of Nebraska-Lincoln (https://astro.unl.edu/interactives/)

1. Which star appears the brightest?
2. Which star has the greatest luminosity?
3. Which star appears the dimmest?
4. Which star has the least luminosity?
5. Rank the stars from closest to farthest away. Explain your reasoning.

Summary

If an object has a lower (more negative) absolute magnitude but appears dimmer, that means the object is _____ away.

1. Fill in the blanks in the table to identify the fraction of light received at each distance. Explain your reasoning below the table.

   Activity Credit: Astronomy Interactives from the Astronomy Education Department at the University of Nebraska-Lincoln (https://astro.unl.edu/interactives/)

Fraction of Light Received at Different Distances

Distance	Fraction of Light Received
	1
	1/9
4	

Distance	Fraction of Light Received
1	
	1/4
3	

Reasoning

2. Fill in the blanks in the table to identify how distance, luminosity, and apparent brightness are related.

   Activity Credit: Astronomy Interactives from the Astronomy Education Department at the University of Nebraska-Lincoln (https://astro.unl.edu/interactives/)

Distance, Luminosity, and Apparent Brightness Relationships

Distance	Luminosity	Apparent Brightness
1		1
	2	2
2	4	
2		3/4
3	6	
	3	1/3

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3.4: Luminosity Plots

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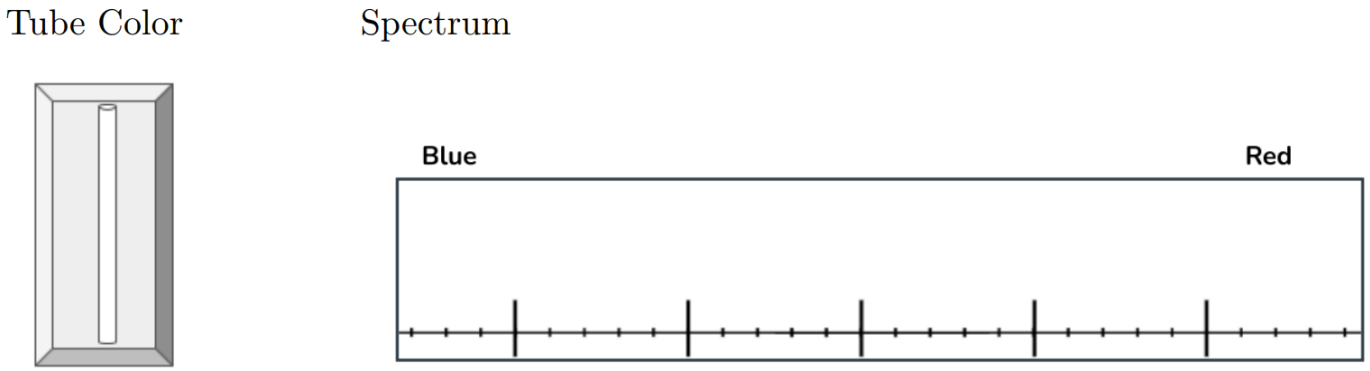
3.5: Spectroscopy

3.7.1 Discrete Spectra

Model

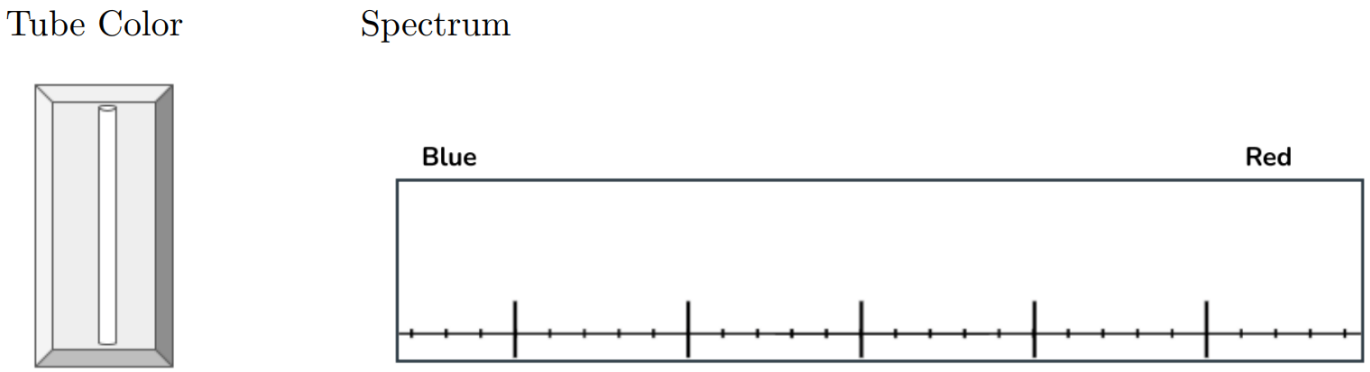
Shade in the spectrum tube based on the color without using the diffraction grating. Then, sketch the spectrum of the light using the diffraction grating. If you do not have physical tools, you can do this using the Spectroscopy Simulator from the Foothill AstroSims website: https://foothillastrosims.github.io/Spectroscopy-Demonstrator/

Hydrogen



Hydrogen discharge tube and observed emission spectrum through a diffraction grating.

Helium



Helium discharge tube and observed emission spectrum through a diffraction grating.

1. Does the light from these tubes contain all of the colors?
2. Are the lines from each source the same or different?
3. How many lines did each source emit?

Summary

The emission spectrum that you observed is different from the blackbody spectrum that we explored earlier:

An emission spectrum contains _____.

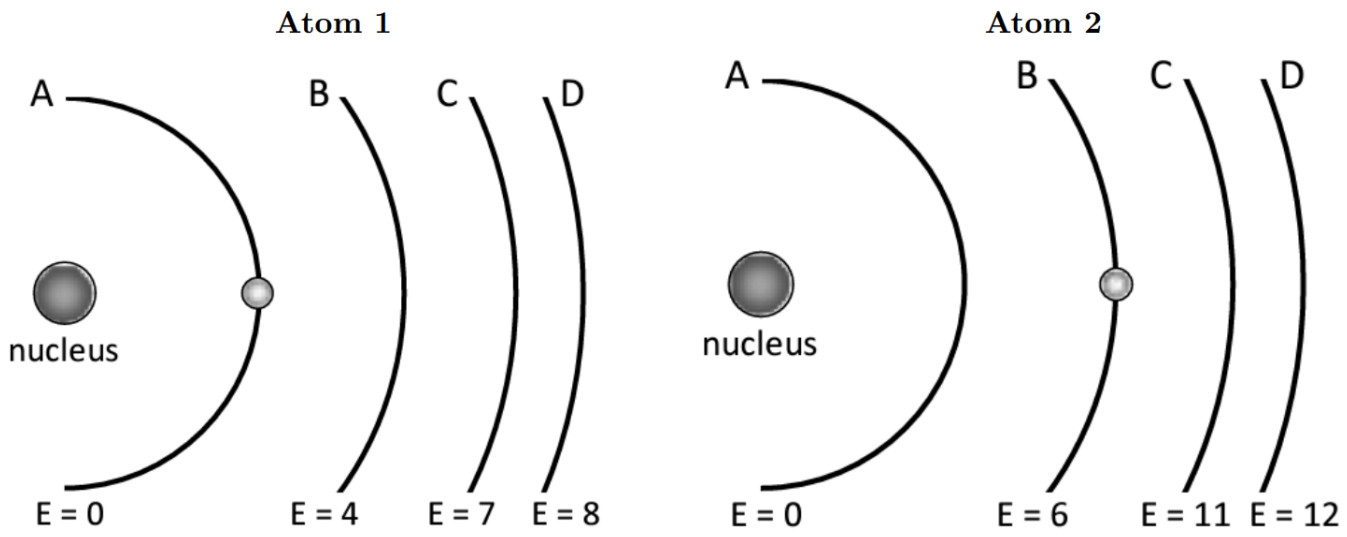
An emission spectrum depends on the _____ of the object and does not depend on the _____ of the object.

A blackbody spectrum contains _____.

A blackbody spectrum depends on the _____ of the object and does not depend on the _____ of the object.

3.7.2 Atomic Orbitals

Model



Two atoms showing electron energy levels and orbital transitions for comparison.

Image Credit: Astronomy Ranking Task from Rica Sirbaugh French at MiraCosta College (https://home.miracosta.edu/rfrench/facultyshare/RTs.html)

1. Is the lowest energy state near the nucleus of the atom or far away from the nucleus of the atom?
2. Which atom will need to absorb more energy to transfer an electron from its ground state (lowest energy state) to the first excited state? How much energy does this process take in each atom?
3. How much energy is gained or lost (identify one) when an electron transitions from C to B in each atom?
4. When atoms lose energy, they give off light with a wavelength determined by the amount of energy lost. Will these two atoms have the same spectral lines? Explain your thinking.

Summary

The ground state is the _____.

The first excited state is _____.

When atoms absorb photons electrons transition closer to / farther from the ground state: _____.

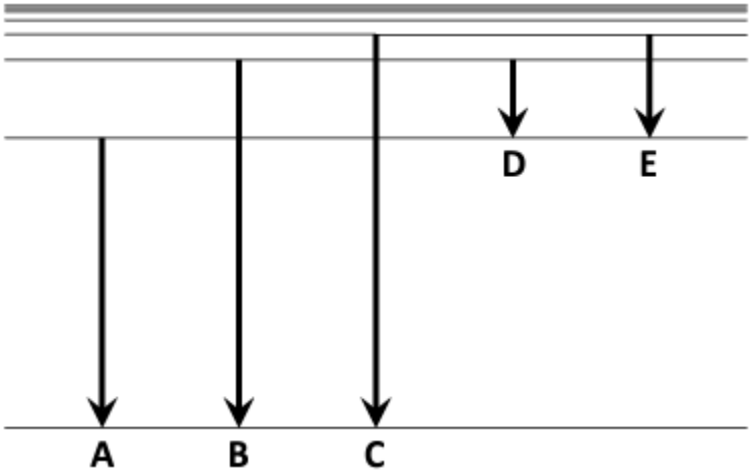
When atoms emit photons electrons transition closer to / farther from the ground state: _____.

The energy levels are _____ for different atoms, which is why atoms have _____ spectra.

3.7.3 Emission

Model

The lines below represent similar energy levels as the previous model. The bottom line is the ground state, closest to the nucleus of the atom. The length of the arrows represents the amount of energy released by the atom as a photon.



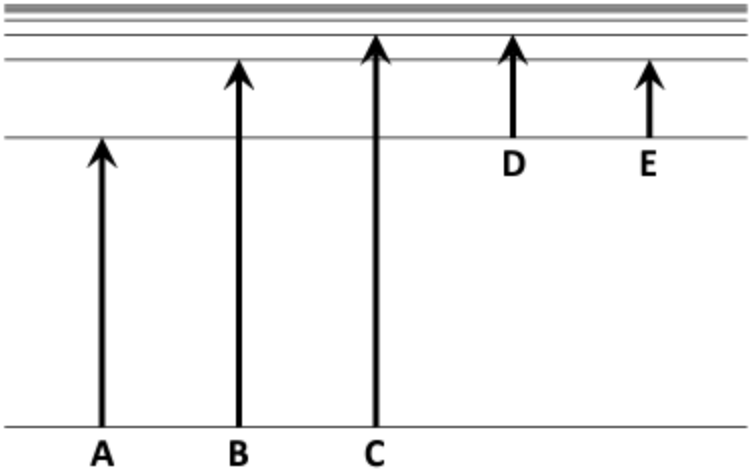
Electron energy level diagram showing emission transitions and photon energies.

Image Credit: Astronomy Ranking Task from Rica Sirbaugh French at MiraCosta College (https://home.miracosta.edu/rfrench/facultyshare/RTs.html)

1. As you get farther from the ground state (bottom), are the lines closer together or farther apart?
2. Which transitions end on the ground state?
3. Which transitions end on the first excited state?
4. Which transitions are the largest?
5. Complete the sentence: Higher energy photons are released for transitions that end at the _____ state.

3.7.4 Absorption

Model



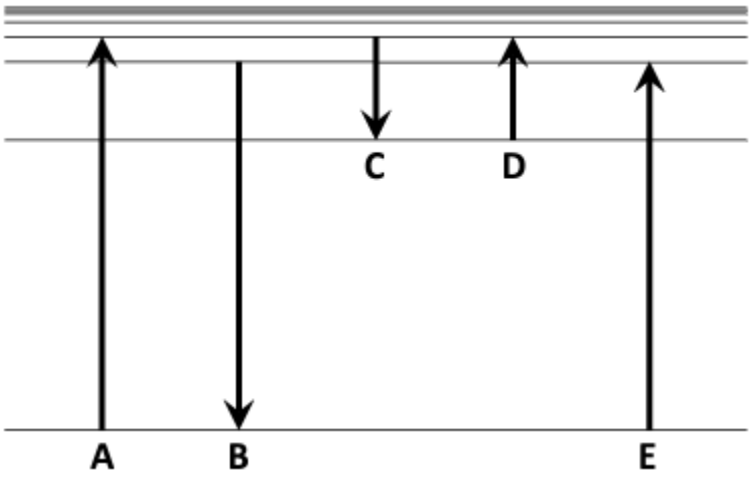
Electron energy level diagram showing absorption transitions to higher states.

Image Credit: Astronomy Ranking Task from Rica Sirbaugh French at MiraCosta College (https://home.miracosta.edu/rfrench/facultyshare/RTs.html)

1. Are these transitions to lower or higher energy states?
2. If an atom absorbs a low-energy photon, what transitions might occur?
3. If an atom absorbs a high-energy photon, what transitions might occur?
4. Electrons typically remain at the ground state. If that is the case, which transition would represent the minimum amount of energy needed to change the state of the electron?

3.7.5 Electron Transitions

The models below represent different transitions within a single atom.



Electron transition diagram with labeled paths for absorption and emission analysis.

Image Credit: Astronomy Ranking Task from Rica Sirbaugh French at MiraCosta College (https://home.miracosta.edu/rfrench/facultyshare/RTs.html)

1. Which letters represent absorption of light? Rank them from largest to smallest amount of energy gained.
2. Which letters represent emission of light? Rank them from largest to smallest amount of energy gained.

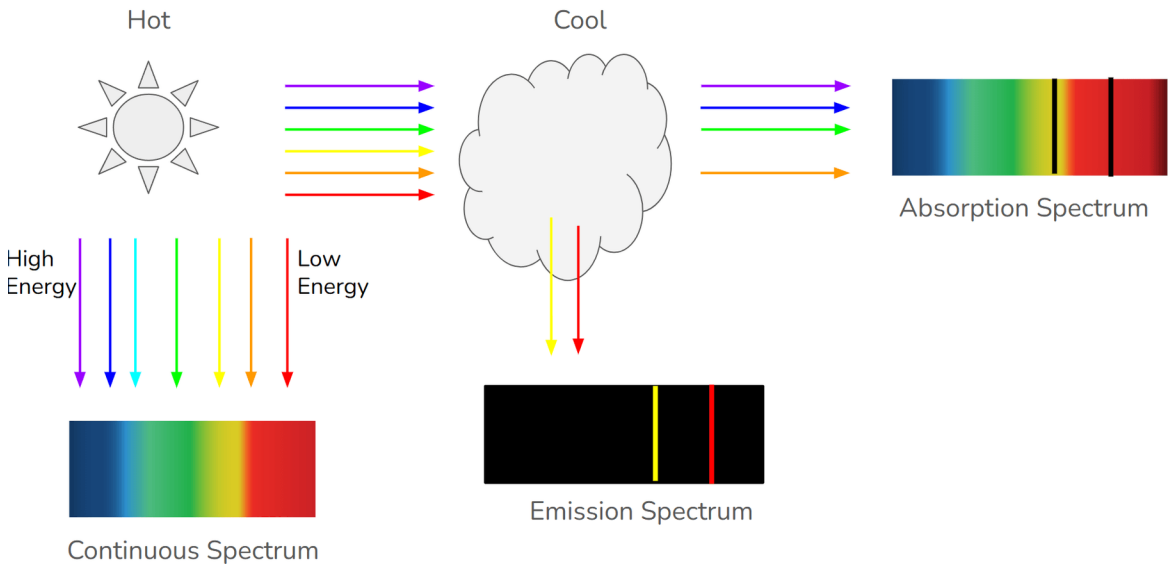
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3.6: Applications of Spectroscopy

3.8.1 Types of Spectra

Model

The model below shows the three types of spectra



Hot star, cool gas cloud, and resulting continuous, emission, and absorption spectra.

1. What colors of light are given off by the star?
2. Do all of those colors pass through the cool cloud? If not, what happens to those colors?
3. When a hot object radiates light due to its temperature, what type of spectrum does it give off?
4. When light passes through a cold gas, what type of spectrum do you see if you are looking at the light that passes through the gas from the source?
5. When light passes through a cold gas, what type of spectrum do you see if you are looking at the light emitted from that gas, not the original source?
6. Use the model images in class to match the spectrum to the Energy Output Plot on the next page.

3.8.2 Blackbody Radiation Plots

Model

The simulation below shows the amount of light each section (power) for each wavelength of light. The peak of the red curve shows which wavelength is emitted the most. Explore the simulation below:

- Change the temperature to see how the red curve changes up/down and left/right
- Zoom in or out as needed to see the data
- Examine the star color, which is right next to the B, G, R circles above the graph

Simulation Source: https://phet.colorado.edu/sims/html/blackbody-spectrum/latest/blackbody-spectrum_all.html

1. When the temperature increases, does the curve get taller/shorter? Does it get wider/narrower?

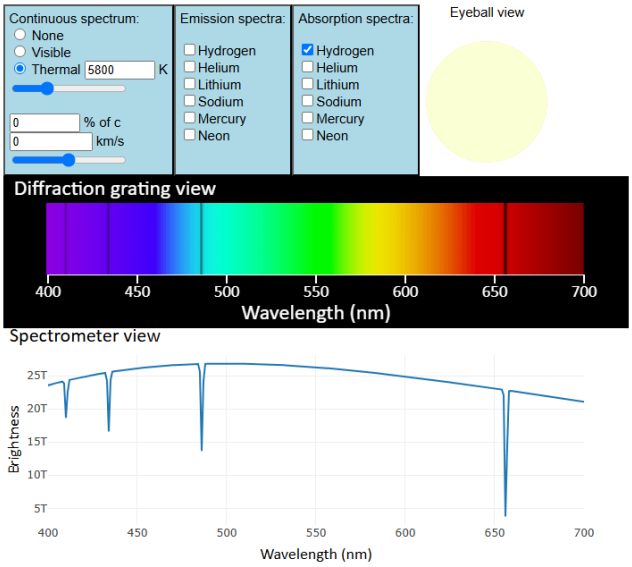
2. When the temperature increases, does the peak of the curve move left or right? Is this towards a higher or lower wavelength?
3. Are all visible wavelengths emitted at any temperature? You might need to zoom in to check if some are nonzero.
4. Is this a **continuous spectrum**, **emission spectrum**, or **absorption spectrum**? Explain how you know.
5. If you saw two curves, how could you tell which one represented a hotter star? Be specific.

1.3 Radiation Plot with Absorption and Emission Spectra

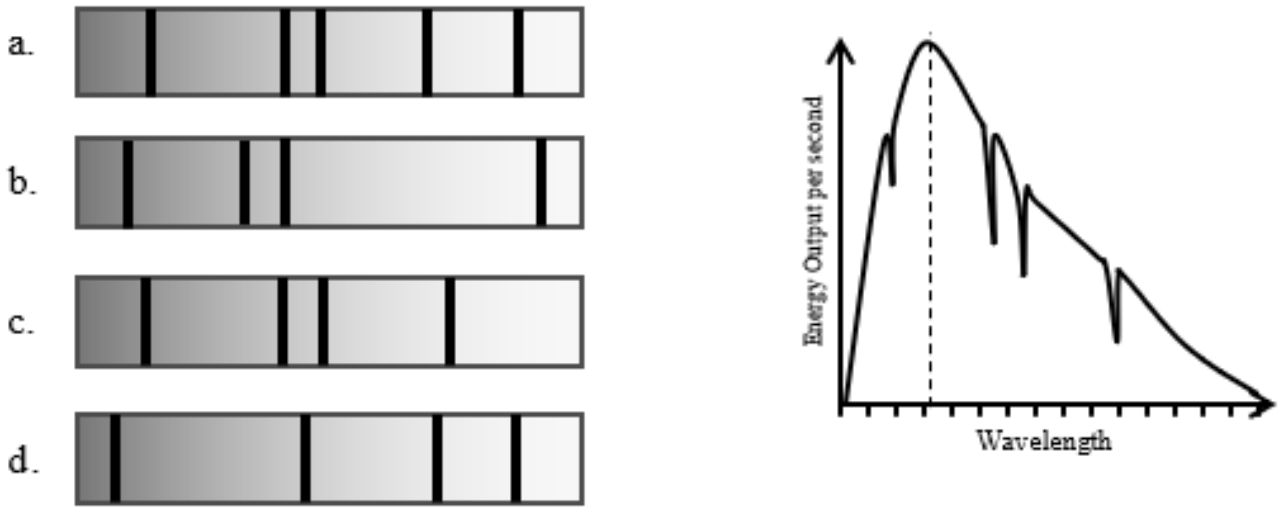
Model

Go to the Spectrum Constructor fromFoothill AstroSims: https://foothillastrosims.github.io/...m-Constructor/

- Select **Thermal** and adjust the temperature. This is a zoomed in (flatter) plot of what you explored in the PhET Radiation Plot simulator
- Reset the temperature 5800K. This is the surface temperature of our sun
- Select **Hydrogen** on the **absorption spectra** panel.
- Explore other elements one at a time in the absorption spectra panel

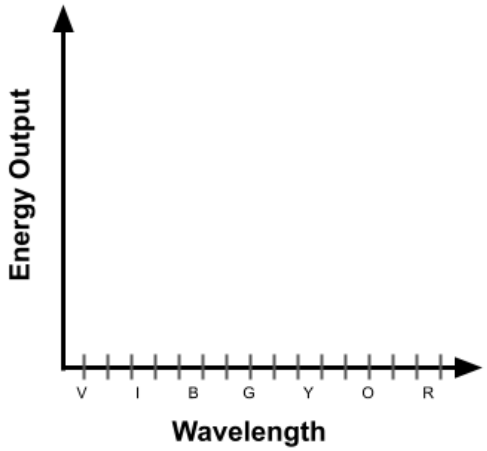


1. How does the Diffraction Grating image compare to the Spectrometer View graph?
2. Choose an element and compare its **Emission Spectrum** to its **Absorption Spectrum** (only have one checked at a time). Describe similarities and differences between the two spectra
3. Four different reference spectra are shown for different elements (a–d). On the right, there is a blackbody radiation plot.
    1. Which spectrum do the lines on the radiation plot match? Explain your thinking.
    2. Is the plot an **emission** or **absorpotion** plot? Explain your reasoning.
    3. How would the energy output look different for the opposite (absorption or emission) of light at those wavelengths? Explain your reasoning and draw it on the blank template below.



Four reference spectra and a blackbody radiation plot with absorption features.

Image Credit: Center for Astronomy Education (CAE) (https://www.as.arizona.edu/cae/materials_resources/)



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4: STARS

4.1: Our Sun
4.2: HR Diagram
4.3: Birth of a Solar System
4.4: Fusion
4.5: Beyond the Main Sequence
4.6: Stellar Evolution
4.7: Stellar Graveyard

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4.1: Our Sun

4.1.1 Observing Our Sun

Model A

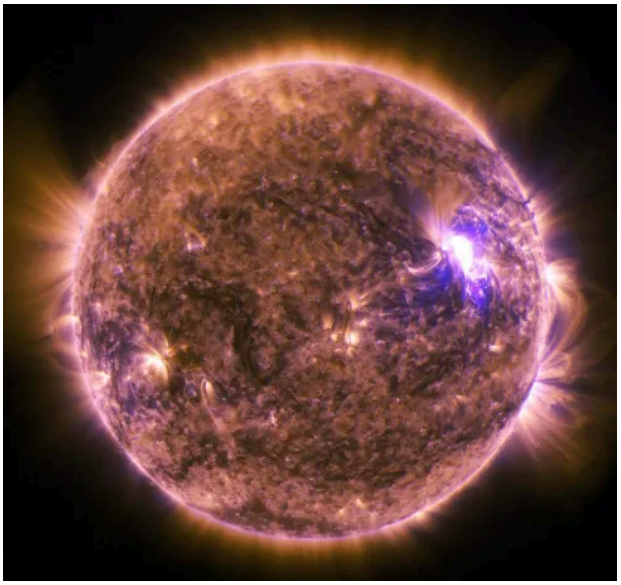


Image Credit: OpenStax Astronomy 2e (https://openstax.org/details/books/astronomy-2e) taken from NASA/SDO

- What do you notice when you look at this image of the sun?
- What do you wonder about what you see?

Model B

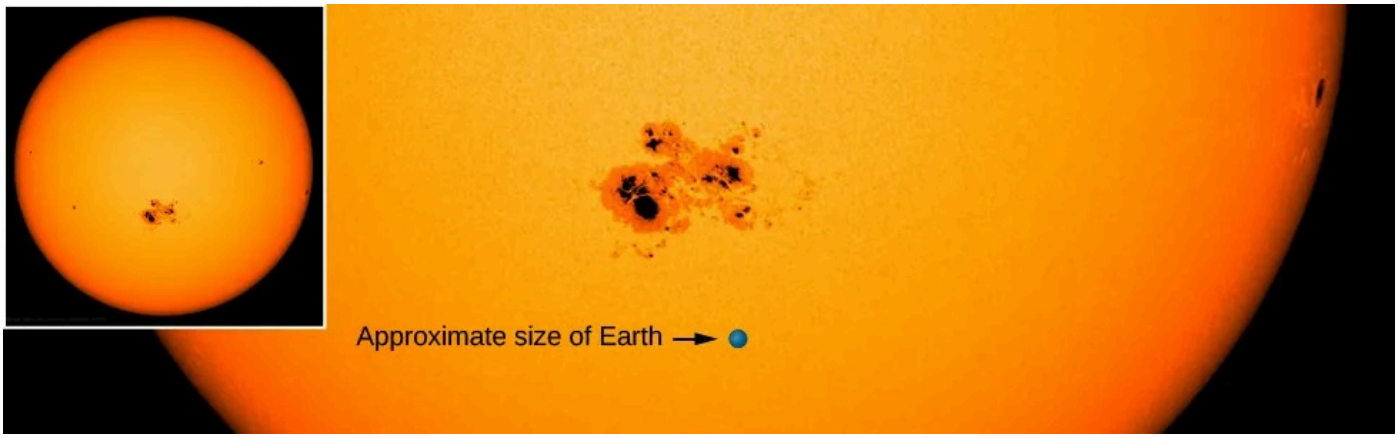


Image Credit: OpenStax Astronomy 2e (https://openstax.org/details/books/astronomy-2e)

- What do you notice when you look at this image of the sun?
- What do you wonder about what you see?

Model C

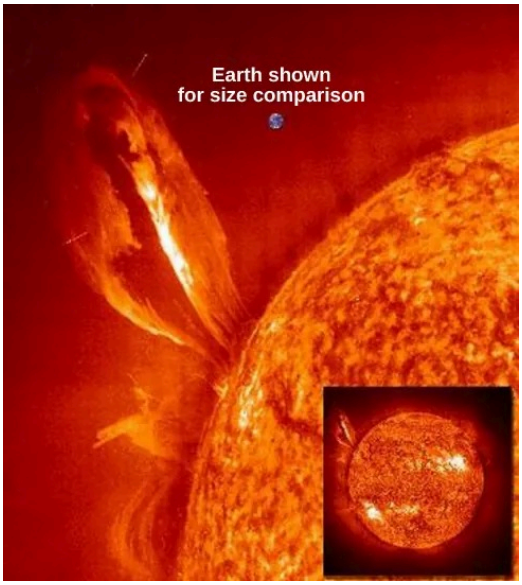


Image Credit: OpenStax Astronomy 2e (https://openstax.org/details/books/astronomy-2e) modification of work by SOHO/EIT/ESA

- What do you notice when you look at this image of the sun?
- What do you wonder about what you see?

4.1.2 Layers of the Sun

Model A

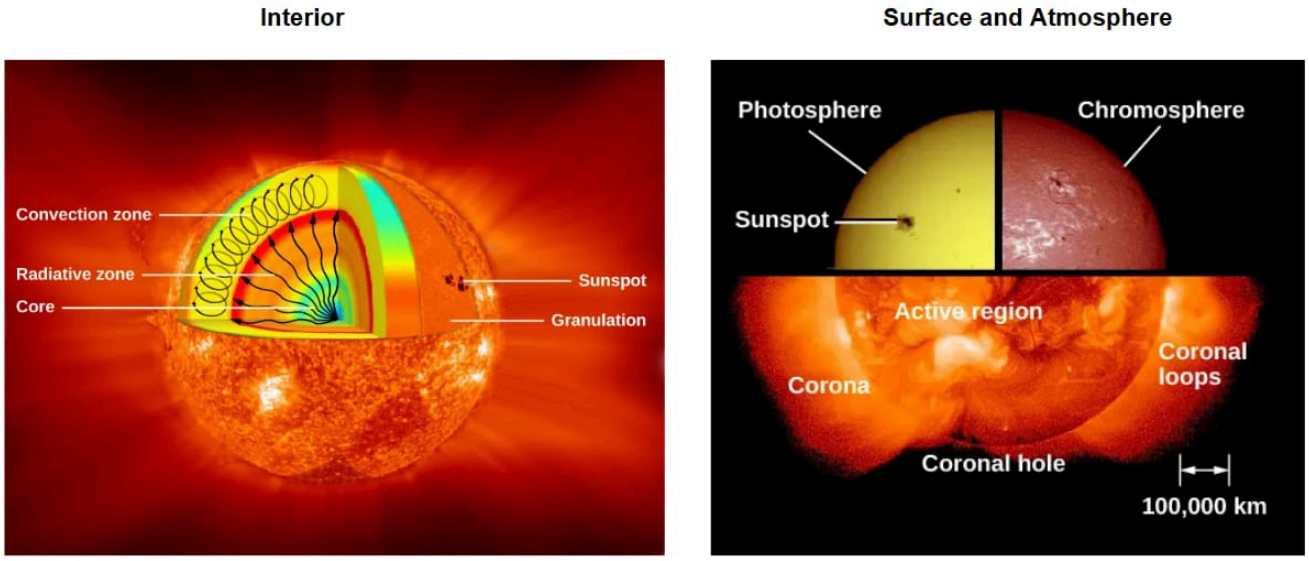


Image Credit: OpenStax Astronomy 2e (https://openstax.org/details/books/astronomy-2e) modification of work by NASA/Goddard

1. How many layers does the sun have?

2. Which layers do you think are considered the atmosphere of the sun?

Model B

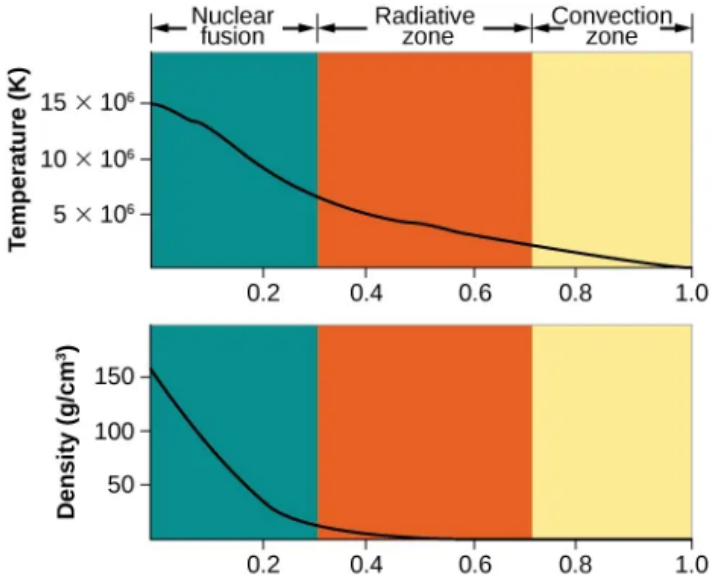


Image Credit: OpenStax Astronomy 2e (https://openstax.org/details/books/astronomy-2e)

1. What region of the sun has the highest density? What region of the sun has the highest temperature?
2. Describe the trends in density. How does density change throughout the sun?
3. Describe the trends in temperature. How does temperature change throughout the sun?

4.1.3 Energy Transfer Processes

Model A

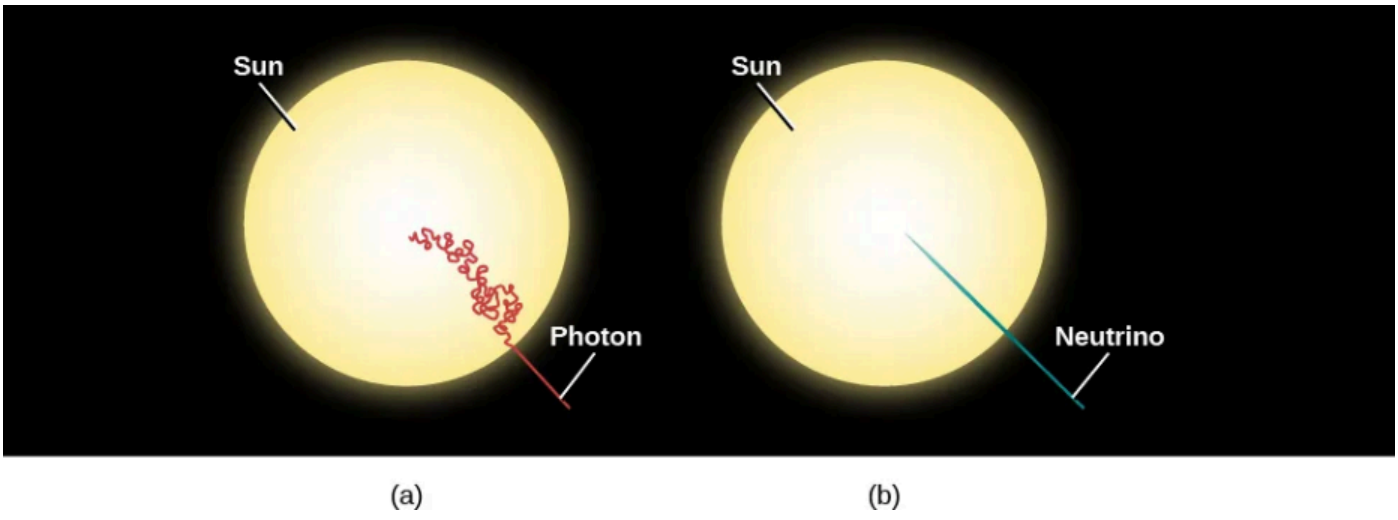


Image Credit: OpenStax Astronomy 2e (https://openstax.org/details/books/astronomy-2e)

1. Describe the differences in the path photons (light) and neutrinos (small particles) that are created in the core of the sun
2. Do you think **neutrinos** or **photons** travel from the core to the surface faster?

Model B

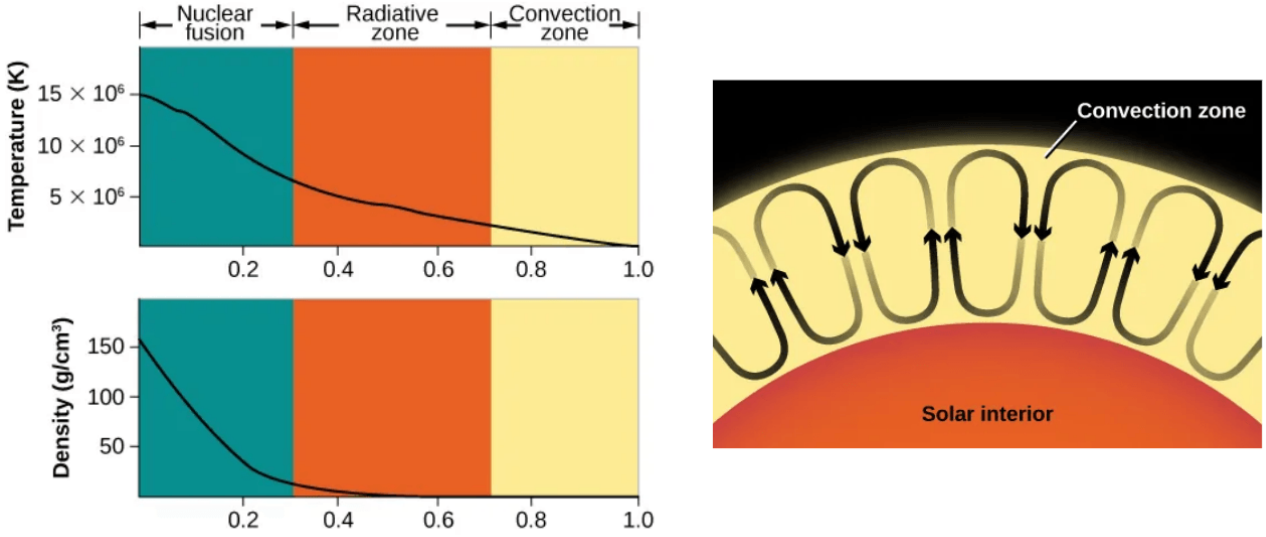
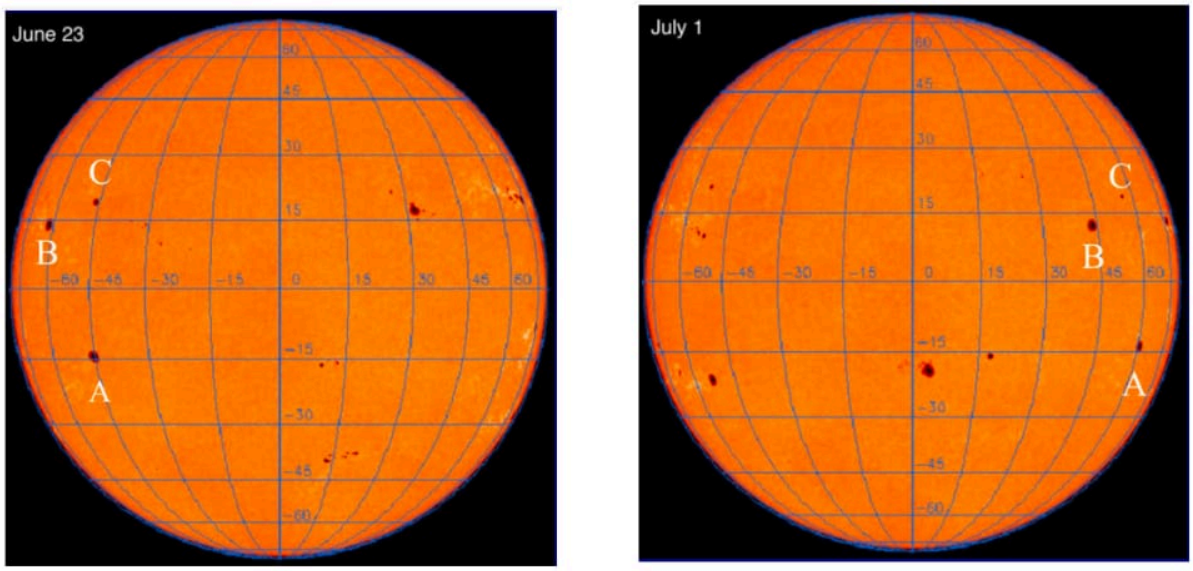


Image Credit: OpenStax Astronomy 2e (https://openstax.org/details/books/astronomy-2e)

1. According to the graph, which part of the **convective zone** is hotter: the inner part (closer to core) or outer part (closer to surface)?
2. Use your answer and the convection zone diagram to determine:
    1. Is the gas in the hotter region rising or sinking?
    2. Is the gas in the colder region rising or sinking?
3. Does this process bring energy from the core to the surface or from the surface to the core? Explain.

4.1.4 Sunspot Rotation

Model



1. **Draw a line connecting each lettered pair of sunspots**
2. How many days went by between the beginning and end positions?
3. Which sunspot traveled the farthest in this time?
4. Which sunspot traveled the fastest? Explain your reasoning

4.1.5 Differential Rotation

Model

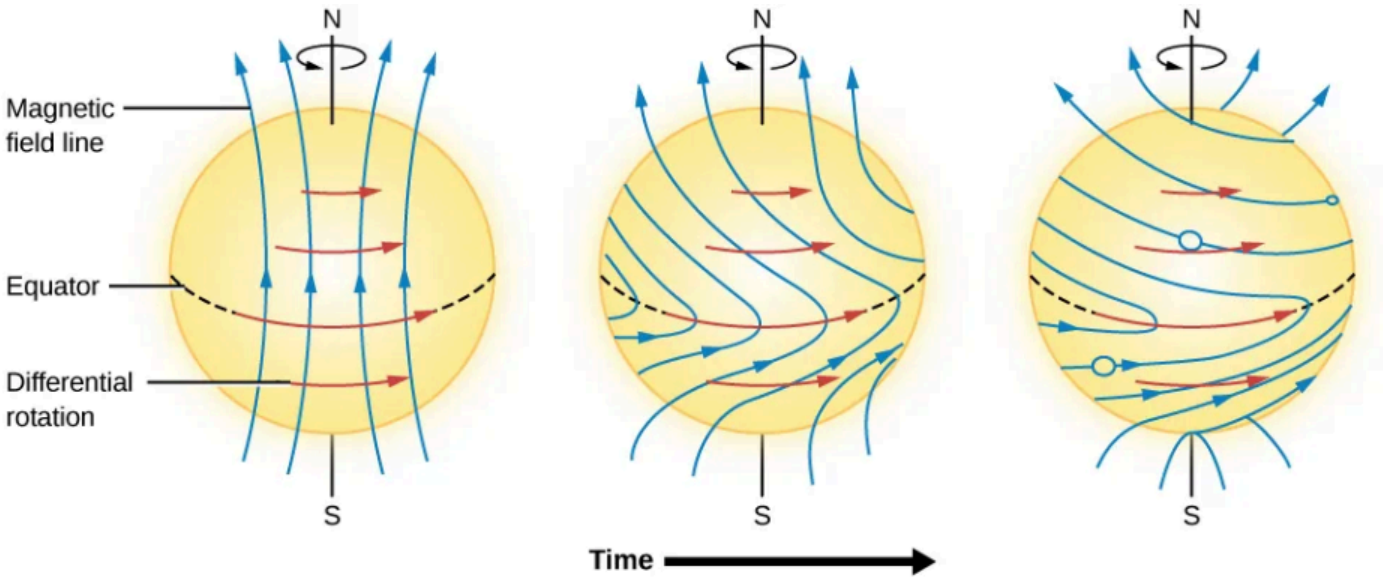


Image Credit: OpenStax Astronomy 2e (https://openstax.org/details/books/astronomy-2e)

1. According to the rotation arrows (red), which part of the sun rotates the fastest?
2. Do the magnetic field lines stay in place or are they dragged with the rotation?
3. What happens to these lines over time? Explain why using information in your response to question 1.

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4.2: HR Diagram

Building an HR Diagram

Instructions

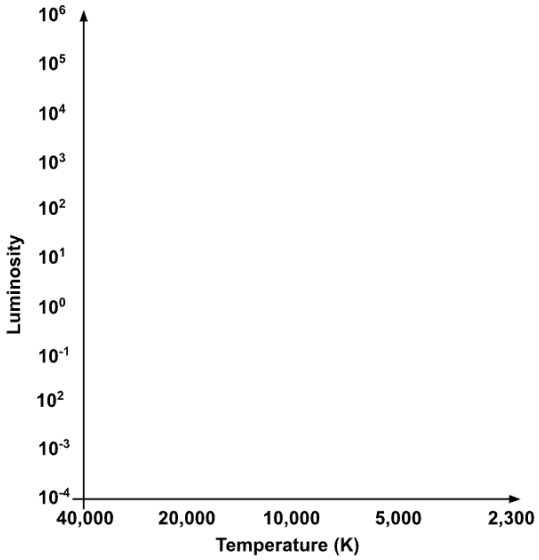
Simulation Setup

- Open the simulation at https://astro.unl.edu/naap/hr/animations/hrExplorer.html
- The red line represents the **Main Sequence** and can be thought of as the starting point of a star's life

Collecting Data

1. Click on different parts of the red line to see a visual of the different stars
2. Draw circles on your results HR Diagram that show:
    1. Size
    2. Color
3. Click around near where you drew your circles and write the value for **Radius** next to them. A radius of 1 means the radius of our sun.
4. **Nearest Stars**
    1. Select **Nearest Stars** and put dots on your diagram to show the general star locations plotted (you do not need to copy every dot exactly)
    2. Click around on some of them to look for common trends about color and size. Add labels to your diagram based on the trends
5. **Brightest Stars**
    1. Select Brightest Stars and put dots on your diagram to show the general star locations plotted (you do not need to copy every dot exactly)
    2. Click around on some of them to look for common trends about color and size. Add labels to your diagram based on the trends
    3. Add radius values next to some of the points to help show trends.
6. **Isoradius Lines**
    1. Make sure the show isoradius lines box is checked
    2. Sketch these lines with their radius values on your diagram
    3. Draw arrows between lines in the direction that radius increases.

Model



1. Where on an HR Diagram are the hottest (most blue) and coldest (most red) stars?
2. How does the size of a star change based on location on an HR diagram?

Comparing Stars on the HR Diagram

Model

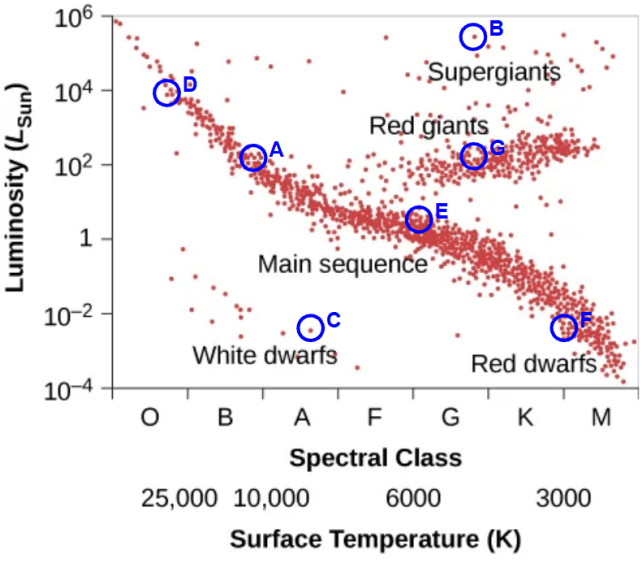


Image Credit: Modified from OpenStax Astronomy 2e (https://openstax.org/details/books/astronomy-2e)

1. What are the spectral type, temperature, and luminosity of Star A
2. Which two pairs of labeled Stars (A-G) in the diagram have the same **temperature**?
3. Do stars of the same **temperature** have the same spectral type? Use a pair of stars from your answer to Question 2 to

support your answer.

4. Which two pairs of labeled stars have the same **luminosity**?

5. If two stars have the same **luminosity** , do they necessarily have the same **temperature**? Use a pair of stars from the H-R diagram to support Your answer.

6. For each of the following star descriptions, state whether the star would be a red giant, red dwarf, white dwarf, or main sequence star, and provide the letter(s) of a star from the H-R diagram that fits each description.

    1. very bright (high luminosity) and very hot (high temperature):

    2. very dim and cool:

    3. very dim and hot:

    4. very bright and cool:

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4.3: Birth of a Solar System

4.3: Birth of a Star

4.3.1 Gas Pressure and Temperature

Model

Interact with the Gas Properties simulation from PhET to explore how temperature and volume (size) relate in gases. Select the **Explore** simulation.

- Add 100 light particles. Do not change this number.
- Note the temperature and pressure of the gas
- Grab the handle on the left side of the container and push the container in to **decrease the volume** of the gas. Note the temperature and pressure of the gas.

Make some claims about a collapsing gas. Use before/after screenshots or data as evidence for your claims.

1. As a gas collapses, the temperature ....
2. As the gas collapses, the pressure ...

Reset the simulation with the same 100 light particles at the initial size and temperature. Now keep the size of the container the same and **add heat** instead. Reset but **cool the gas**. Make a claim about temperature and pressure.

1. As the temperature of a gas increases, the pressure ...
2. As the temperature of a gas decreases, the pressure ...

4.3.2 Hydrostatic Equilibrium

Model

The model below shows two forces that are present on all particles in a star.

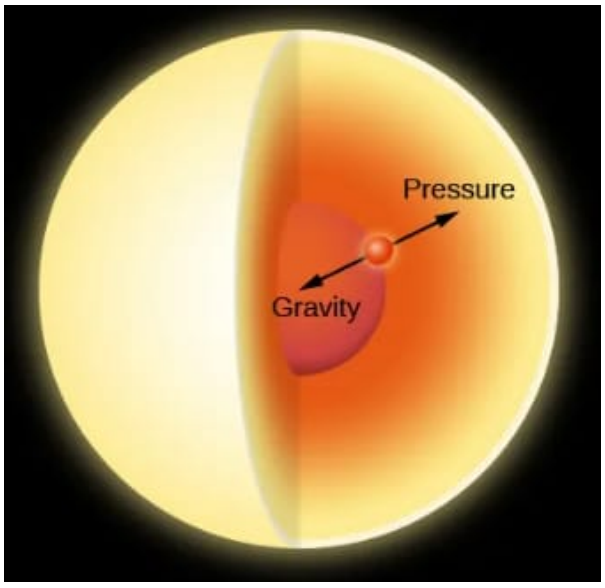
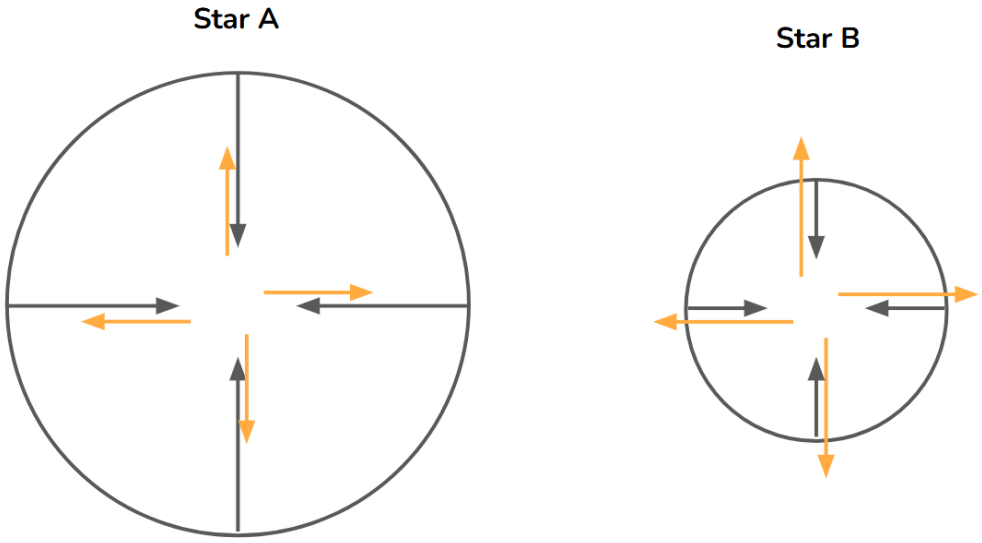


Image Credit: OpenStax Astronomy 2e (https://openstax.org/details/books/astronomy-2e)

1. What force pulls a particle inward? What force pushes a particle outward?
2. What would have to be true about the forces of gravity and pressure if the particles do not fall inward or get pushed outward?
3. Two stars are shown below with their inward and outward arrows (forces). Label each star as either **Gravity Wins** or **Pressure Wins** and then make a claim about whether the star will get bigger, smaller, or remain the same size. Provide clear evidence and reasoning.



4.3.3 Star Birth on an HR Diagram

Model

The HR diagram below shows the path that different protostars take before the begin hydrogen fusion on the main sequence. One stars are on the main sequence, they reach a stable equilibrium of pressure our and gravity in. This is due both to gas pressure and rate of fusion, which increases with temperature. While on the main sequence, the size of the star is stable, but different stars find different equilibrium sizes.

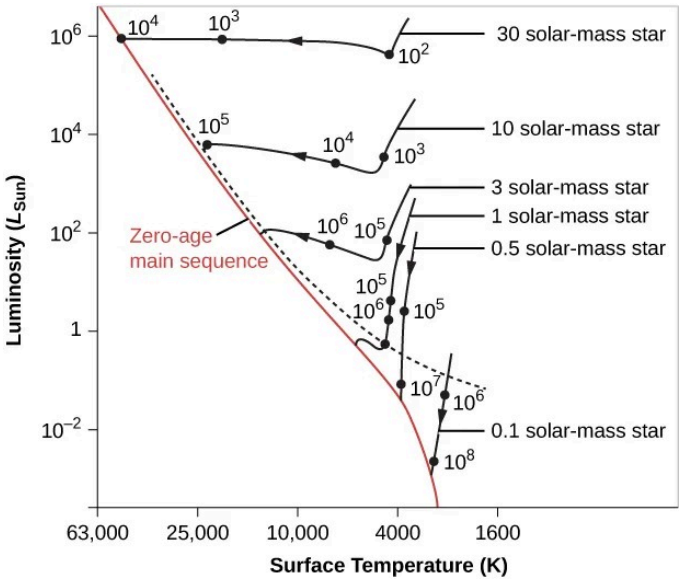


Image Credit: OpenStax Astronomy 2e (https://openstax.org/details/books/astronomy-2e)

1. **Examine the 30 solar-mass protostar:**
    1. Does the luminosity change on its path to the main sequence? Does its temperature change?
    2. Recall $L = \sigma A T^4$. How must its size (area) change along this path?
2. **Examine the 0.5 solar-mass protostar:**
    1. Does the luminosity change on its path to the main sequence? Does its temperature change?
    2. Recall $L = \sigma A T^4$. How must its size (area) change along this path?
3. **Summarize**: What happens to a protostar as it transitions to the main sequence?

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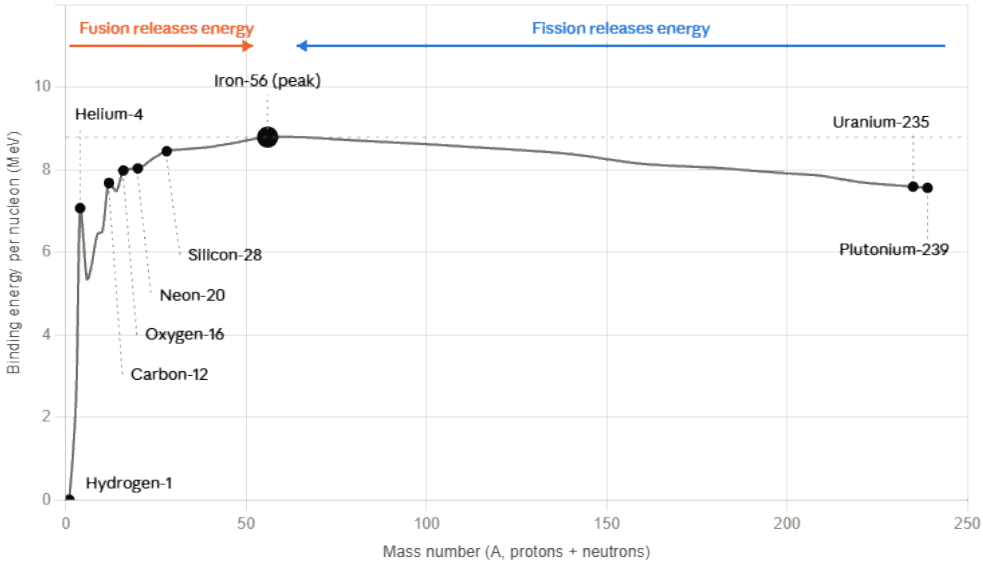
4.4: Fusion

4.4: Fusion

4.4.1 Binding Energy

Model

Below is a graph of the **nuclear binding energy** of different elements All elements ar eon this graph, but only a few are labeled. The y-axis represents the energy **released** when that element is formed.



Trends

1. If you start with hydrogen and end with helium, do you release energy or take in energy? Explain.
2. If you start with helium and ended with lithium, do you release energy or take in energy? Explain.
3. If you have iron, can you release energy or take in energy? Explain.
4. **Summarize:** How can you tell if a process releases energy or takes in energy?

Quantitative Results

1. If you start with hydrogen and end with helium, how much energy is released / taken in?
2. If you start with Oxygen and ended with Carbon, how much energy is released / taken in?
3. If you start with helium and ended with Carbon, how much energy is released / taken in?
4. If you start with Uranium and end with Iron, how much energy is released / taken in?

4.4.1 Proton-Proton Chain

Model

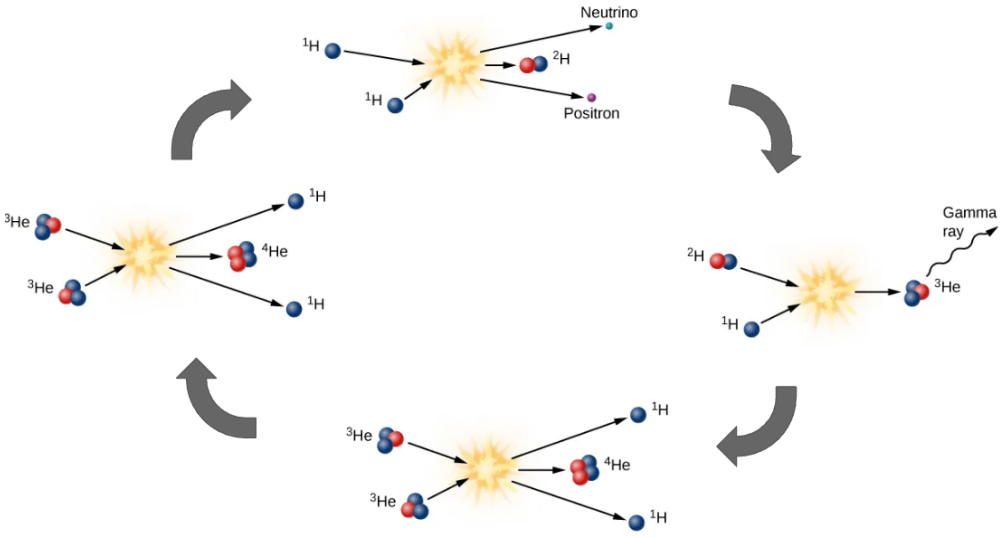


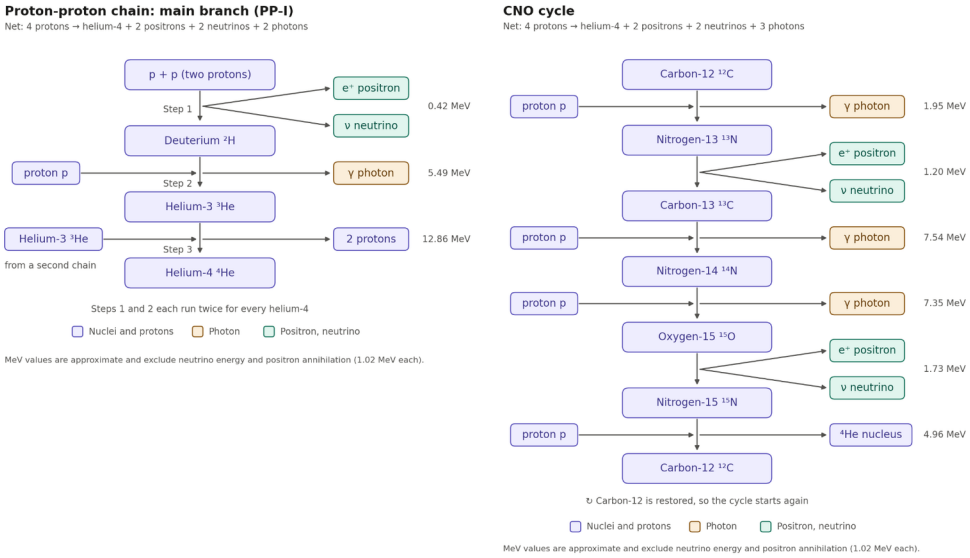
Image Credit: Modified from OpenStax Astronomy 2e (https://openstax.org/details/books/astronomy-2e)

1. Fusion starts with the smallest object coming together to form a bigger object. Label the four diagrams 1-4 to show the order of this cyclical process
2. What two objects combine in the first step of the P-P Chain?
3. What two objects are released in the last step of the P-P Chain?
4. How many total protons are needed to complete this cycle?
5. How many gamma rays γ and how many neutrinos ν are released in this process?

4.4.2 Comparing the P-P Chain to the CNO Cycle

Model

The flowcharts below show two different processes that can occur, depending on the



1. In the P-P chain, how many total protons energy the cycle? **Careful: Steps 1&2 happen twice before two ^{3}He come together in Step 3.**
2. In the P-P chain, how many protons are released at the end? What is the net consumption of protons (in - out)?
3. In the CNO cycle, what is the net consumption of protons?
4. How does the output of each cycle compare? Consider neutrinos, photons, positrons, and any nucleus. **Careful: In the PP Chain, steps 1&2 happen twice in the full process.**
5. In the CNO cycle, does the Carbon get used up? Explain.

4.4.3 Main Sequence

Model

The model below shows how the content of the core of a star changes with time. As a reminder, hydrogen nuclei are **protons** and helium nuclei (^{4}He) contain two protons and two neutrons.

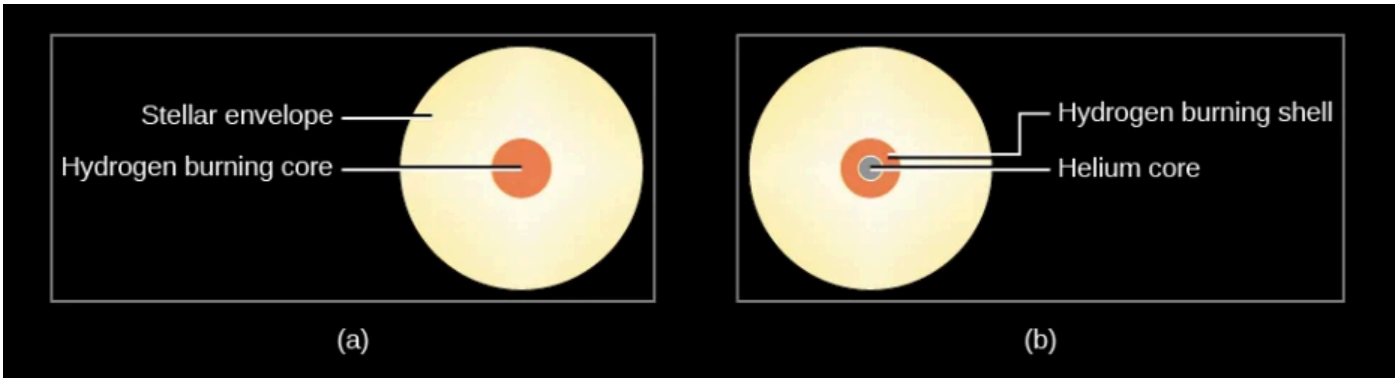


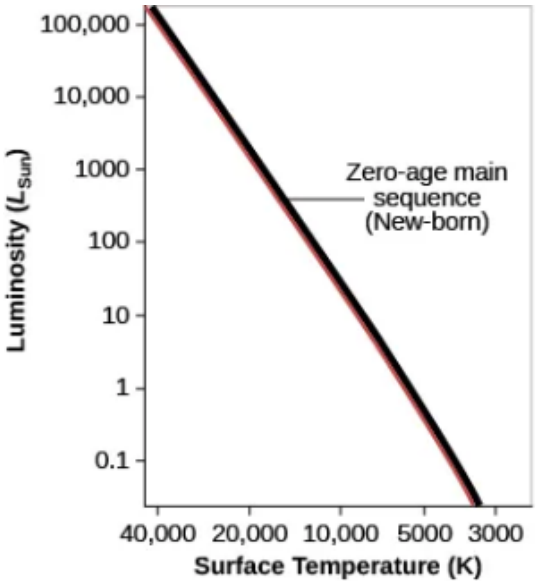
Image Credit: OpenStax Astronomy 2e (https://openstax.org/details/books/astronomy-2e)

1. Where in the star does hydrogen fusion (P-P Chain and CNO cycle) take place?
2. What happens to that hydrogen? How will the core change over time?
3. The **main sequence** begins when hydrogen fusion begins in the core of the star and ends when hydrogen fusion ends. At the end of the main sequence, what is the inner core made of?

4.4.4 Main Sequence Timelines

Model

The model below shows an HR diagram of many stars of different masses that are all "born" (the begin hydrogen fusion) at the same time. The table to the right of the plot gives an approximate amount of time that stars of different mass remain on the main sequence before they use up the hydrogen that is available for fusion (at that time, more will fuse later).



Mass of Star	Time on Main Sequence
0.5 Msun	50,000,000,000 years
1.0 Msun	10,000,000,000 years
2.0 Msun	2,000,000,000 years
6.0 Msun	110,000,000 years
60.0 Msun	360,000 years

Image Credit: OpenStax Astronomy 2e (https://openstax.org/details/books/astronomy-2e)

1. Do higher or lower mass stars last longer? Do higher or lower mass stars have more total fuel to fuse?
2. Based on your answers, do you think that the rate of nuclear fusion in a high-mass star is greater than, less than, or equal to the rate of nuclear fusion in a low-mass star?
3. Remind each other where high and low mass stars are on the HR diagram and place a dot (approximately) on the HR diagram for each star in the table. Label the dots with their mass.
4. Use your responses to the earlier questions to write a number order (1-5) to indicate the order in which each star completes

its main sequence time (ie, put a 1 next to the star that will end its main sequence phase first).

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4.5: Beyond the Main Sequence

4.6: Beyond the Main Sequence

4.6.1 Globular Cluster Turnoff Points

Model

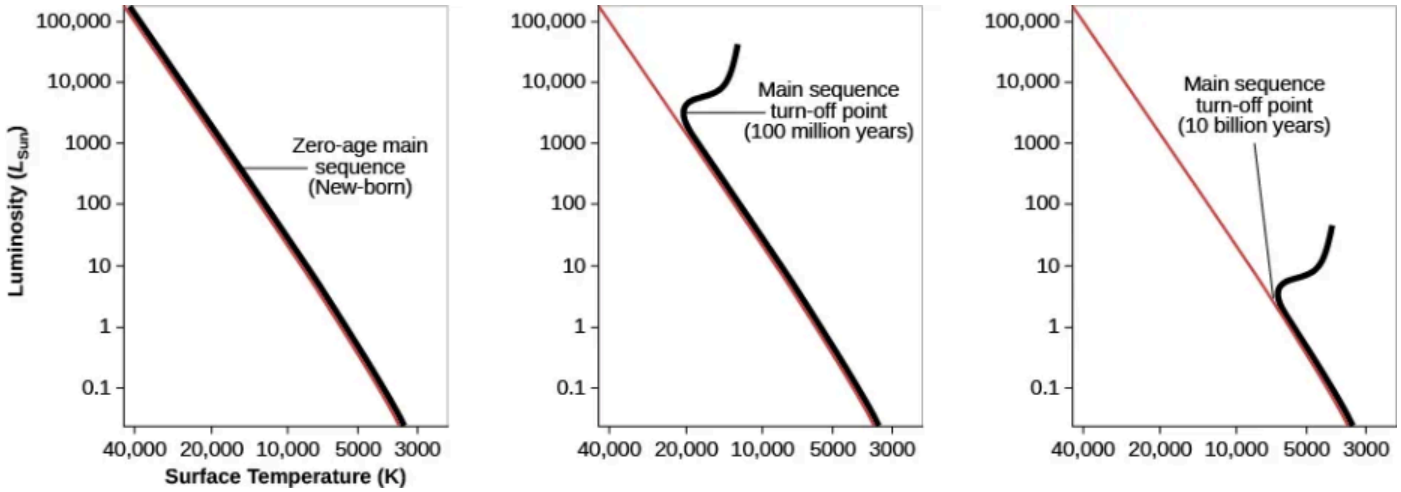


Image Credit: OpenStax Astronomy 2e (https://openstax.org/details/books/astronomy-2e)

1. After 100 million years, which stars are no longer on the main sequence? **Highlight all that apply.**
    1. Higher mass/luminosity stars (top of the main sequence)
    2. Middle mass/luminosity stars (middle of the main sequence)
    3. Lower mass/luminosity stars (bottom of the main sequence)
2. After 10 billion years, which stars are no longer on the main sequence? **Highlight all that apply.**
    1. Higher mass/luminosity stars (top of the main sequence)
    2. Middle mass/luminosity stars (middle of the main sequence)
    3. Lower mass/luminosity stars (bottom of the main sequence)
3. How does the turn-off point change with time? Can you use the turnoff point to determine the age of the cluster?

4.6.1 Globular Cluster Age Ranking

Model

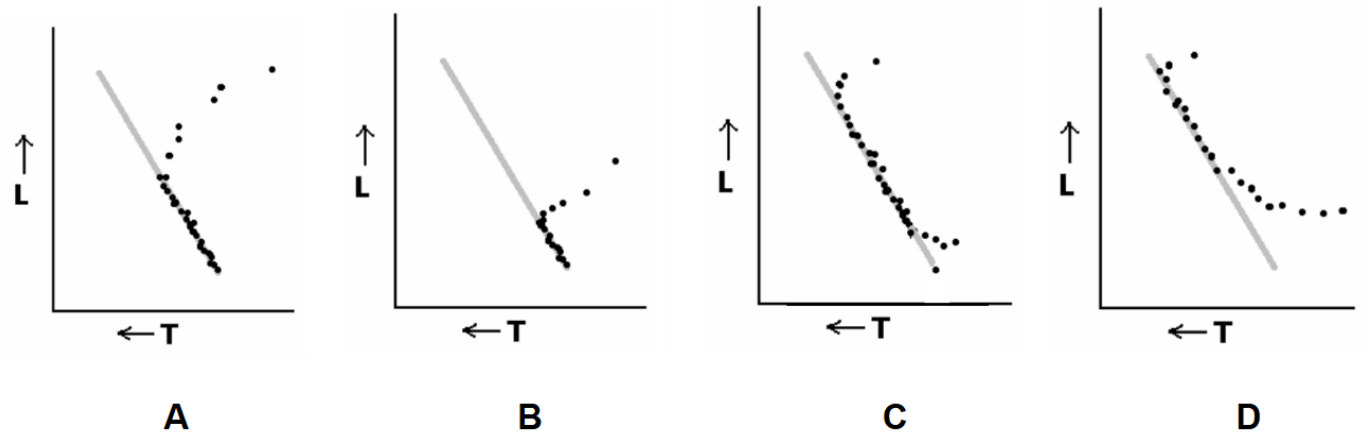
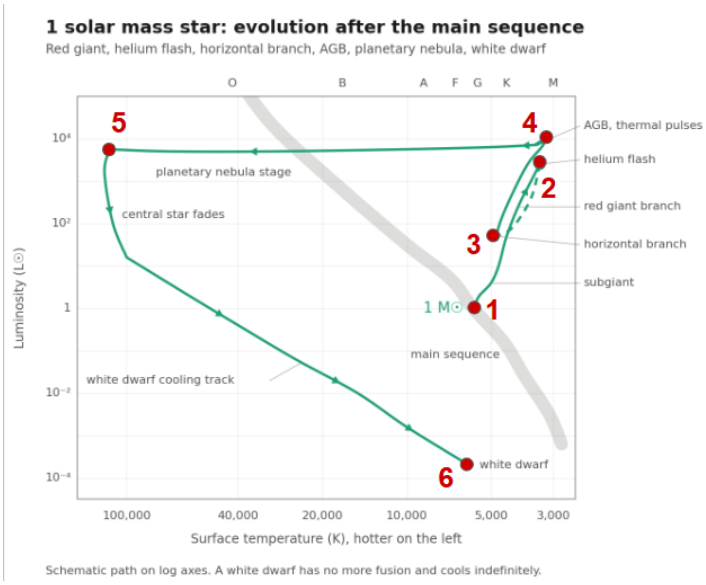


Image Credit: Astronomy Ranking Task from Rica Sirbaugh French at MiraCosta College (https://home.miracosta.edu/rfrench/facultyshare/RTs.html)

1. Rank the images of a star cluster from earliest to oldest. Explain your reasoning
2. Draw each star cluster by making a bunch of circles to represent the dots on these HR diagrams.
    1. Scale them to show bigger vs smaller stars. They cannot be accurately to scale, but you can show relative size
    2. Color them blue, yellow, and red based on their position on the HR Diagram.

4.6.3 Red Giant Branch (1 to 2)

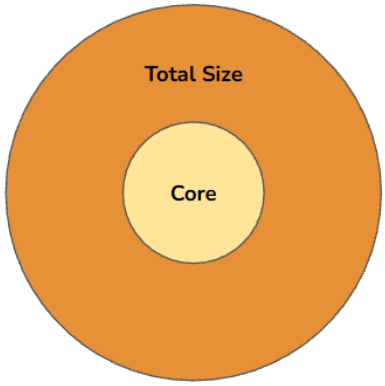
Model



The path from point 1 to 2 is the **Red Giant** branch of stellar evolution for **low mass stars** like our sun.

1. How does the **temperature** of the star changes along the Red Giant Branch?

2. How does the **luminosity** of the star changes along the Red Giant Branch?
3. Recall $L = \sigma AT^4$. How must its size (area) change along this path?
4. This process occurs when fusion in the core stops. If there is no more fusion in the core, will it expand, collapse, or remain the same size? Explain your reasoning.
5. Use your responses to questions 1-4 to show how the core and total star change in size compared to the reference below:

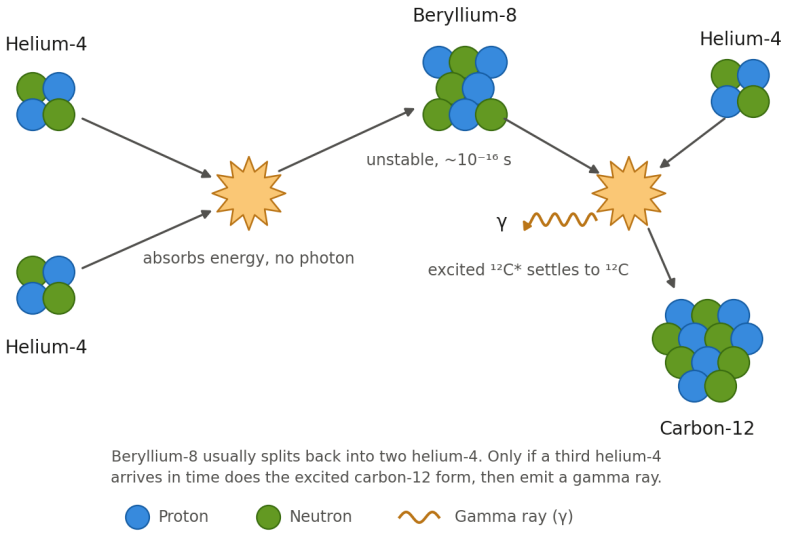


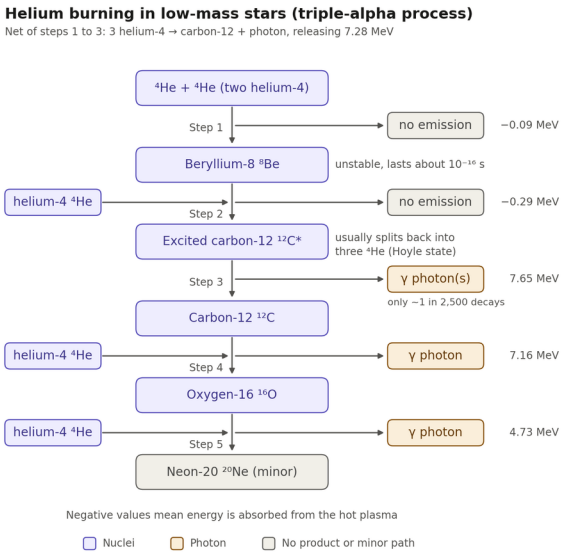
Main Sequence
(do not change)

4.6.4 Helium Fusion - the Triple Alpha Process

Model

Helium nuclei (two protons an two neutrons) are called **alpha particles** in physics and astronomy. The diagram and flow chart below models the process of Helium fusion, which requires much higher temperatures and pressures than hydrogen fusion.





1. Circle the Helium-4 nuclei in the diagram. Why is this process called the **triple alpha process**?
2. What element do the Helium nuclei become?
3. Is there any other particle / element left over (besides your answer to question 2)?
4. Does this process take in or release energy? How does that amount of energy compare with the energy released when hydrogen fuses into helium (26.7 MeV)?
5. How much time is there after step 1 for step 2 to occur?
6. Does step 3 usually result in energy out? Or is that a rare occurrence? Explain.

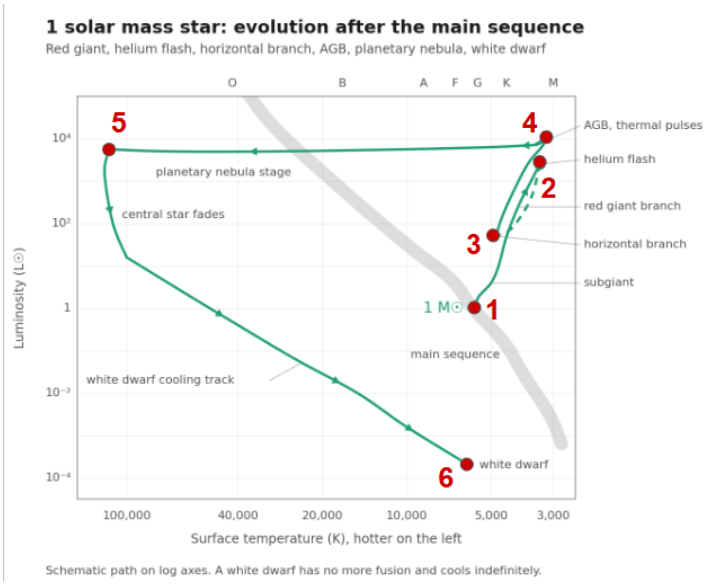
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4.6: Stellar Evolution

4.6: Stellar Evolution

4.6.1 Low Mass Stars - Horizontal Branch and Asymptotic Branch

Model



Horizontal Brach (2 to 3)

1. How does the temperature of the star changes along the Horizontal Branch?
2. How does the luminosity of the star changes along the Horizontal Branch?
3. Recall $L = \sigma A T^4$. How must its size (area) change along this path?

Horizontal Brach (3 to 4)

1. How does the temperature of the star changes along the Asymptotic Branch?
2. How does the luminosity of the star changes along the Asymptotic Branch?
3. Recall $L = \sigma A T^4$. How must its size (area) change along this path?

Planetary Nebula (4 to 5)

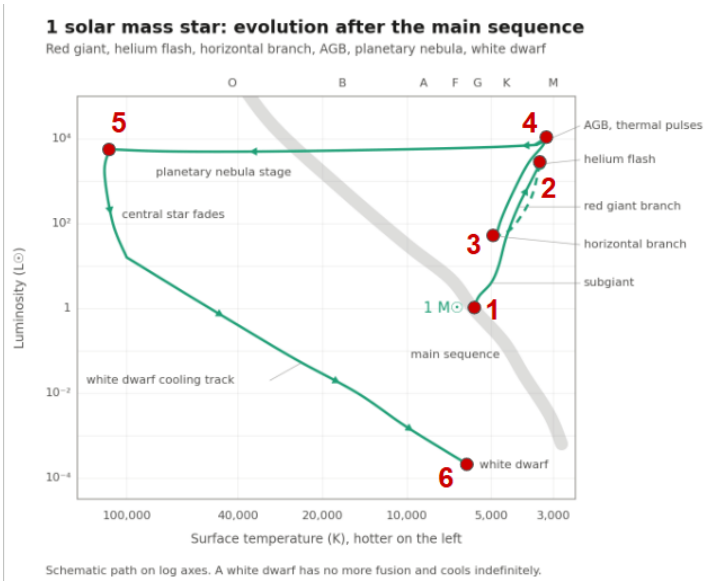
1. How does the **temperature** of the star changes along the path to a Planetary Nebula?
2. How does the **luminosity** of the star changes along the path to a Planetary Nebula?
3. Recall $L = \sigma A T^4$. How must its **size (area)** change along this path?

4. What might be the cause of the change in temperature?

4.6.2 Low Mass Stellar End States

Model

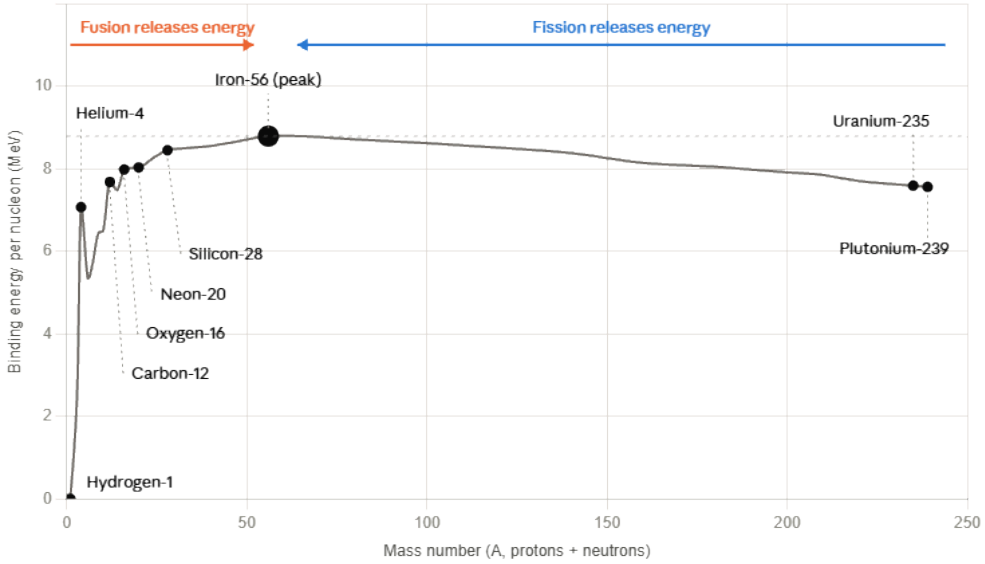
White Dwarf Fades (5 to 6)



1. How does the **temperature** of the star change from 5 to 6?
2. How does the **luminosity** of the star change from 5 to 6?
3. Recall $L = \sigma A T^4$. Is it possible that the size does not change size during this process?

4.6.3 High Mass Stars - Carbon Fusion and Beyond

Model

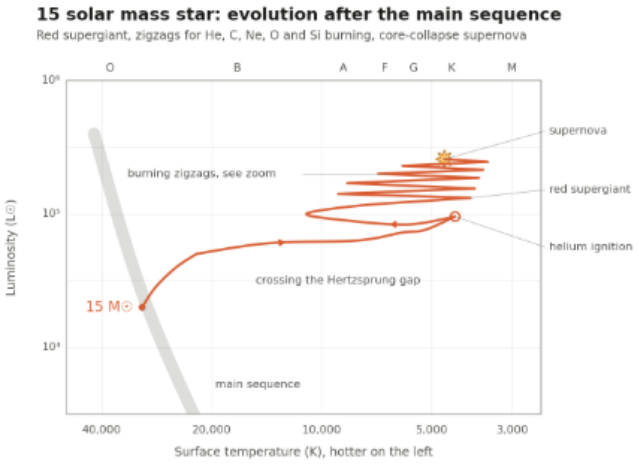


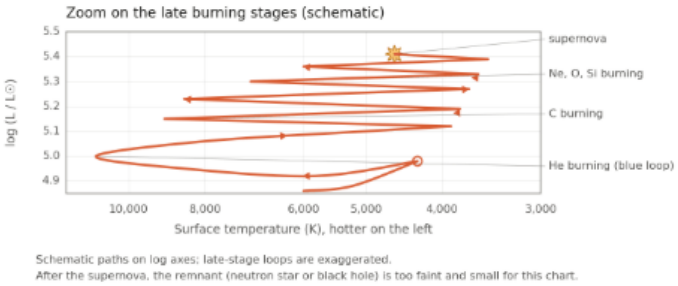
1. Can the Carbon core of the Asymptotic Giant Branch (AGB) star be used as fuel for fusion? If so, what could it fuse into? Explain your thinking.

2. Will there ever be a point where fusion will no longer power stars? Explain.

4.6.4 High Mass Stars - Fusion Cycles

Model





1. When the star moves to the right, does it get bigger or smaller?
2. When the star moves to the right, is the core collapsing or is it stable?
3. When the star moves to the right, is there fusion in the core, or just the shell?

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4.7: Stellar Graveyard

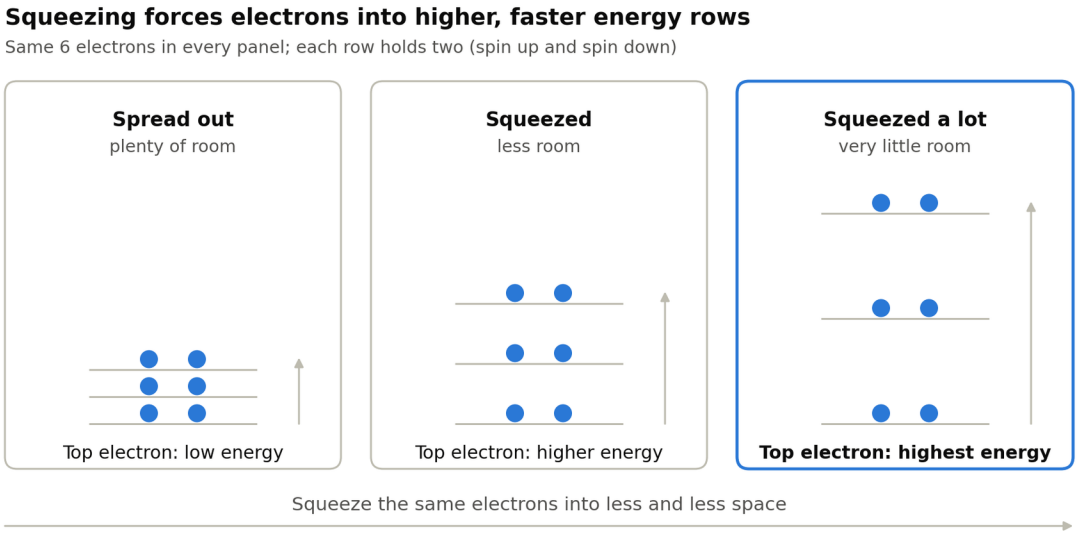
4.7 Stellar Graveyard

4.7.1 Electron Degeneracy Pressure and white dwarfs

Model

A white dwarf has no fusion left, so heat cannot hold it up. Something else pushes outward: its electrons. The rule behind it is the Pauli exclusion principle, which says two electrons cannot share the same quantum state. Picture each energy level as a row in a stadium that holds only two electrons. Electrons fill the lowest rows first. Squeezing them into less space stretches the rows farther apart in energy, so the top electrons end up in much higher rows even though nothing is heating them.

All three panels hold the same six electrons, and each squeeze raises the energy of the top one.



1. The **physical spacing** between electrons **decreases from left to right** in the model images. The model shows **energy levels**. Does the space between energy levels increase or decrease?
2. Which panel has the electron with the most energy? What changed between the panels to cause that?
3. Higher energy electrons are faster electrons and faster electrons hit their surroundings harder. Which panel pushes outward the most?
4. Cooling drops electrons into lower energy levels if there is room for them (only two fit on each row). Will cooling this gas change the energy of the highest energy electrons?
5. A white dwarf cools for billions of years without collapsing. Explain why it doesn't get smaller as it cools.

4.7.2 White Dwarf Mass and Radius

Model

A white dwarf's weight must be balanced by electron degeneracy pressure, and that pressure only rises when the electrons are squeezed closer together. The pressure to balance out gravity is based on **density** not **temperature**.

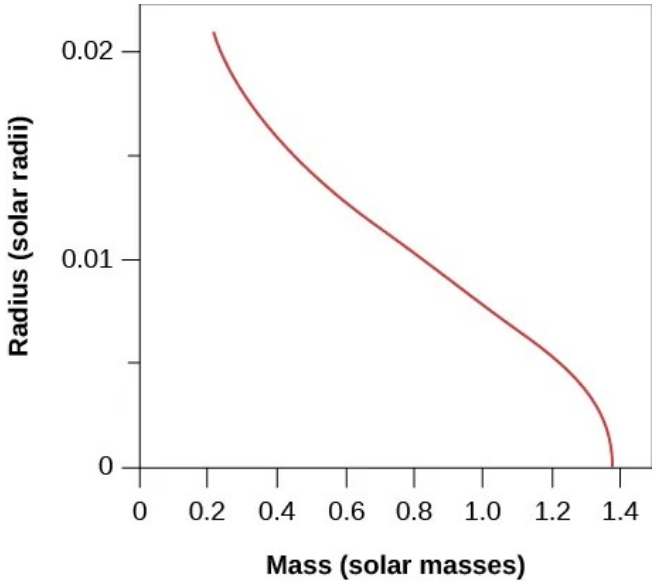


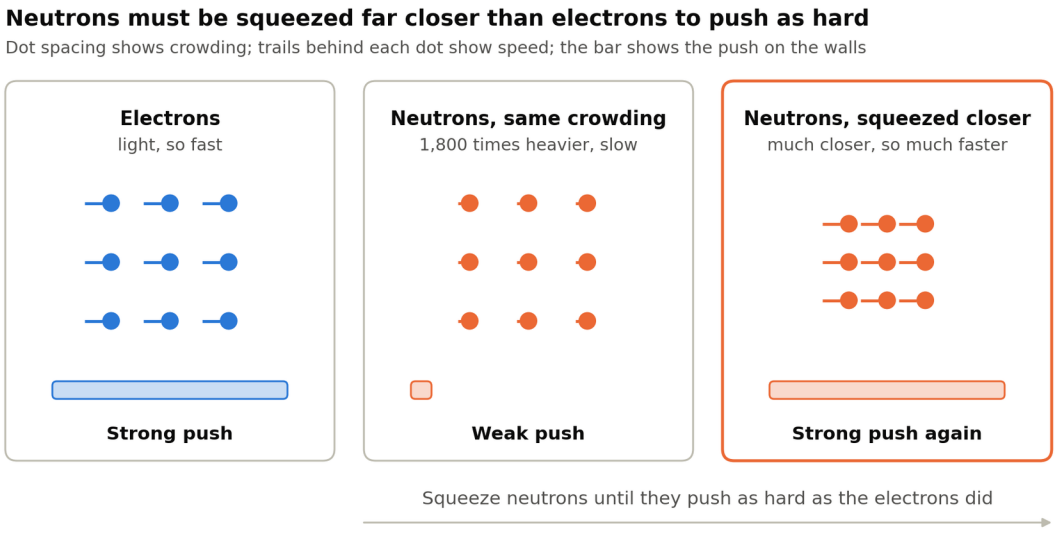
Image Credit: OpenStax Astronomy 2e (https://openstax.org/details/books/astronomy-2e)

1. Place a dot on the curve for the 0.02 radius and 0.01 radius white dwarfs
2. The ratio of the radii for the two dots is 1:2. What is the (approximate) ratio of the masses?
3. What is the largest mass shown in the image? What is the radius at that mass?
4. Electrons get faster as density increases. In a very dense white dwarf approach the speed of light. Why might that put a limit on the maximum mass of the white dwarf?
5. What do you think would happen if more mass was added? **Recall:** This graph shows the radius and mass that result in equal pressure and gravity to make a stable object.

4.7.3 Neutron Degeneracy Pressure and Neutron Stars

Model

If a core is too heavy for electron degeneracy to hold up, gravity squeezes it until electrons are forced into protons. That makes neutrons, and the neutrinos that escape. The core becomes a ball of neutrons, which are also subject to the Pauli exclusion principle, so **neutron degeneracy** pressure takes over from **electron degeneracy** pressure. At the same crowding, electrons and neutrons carry the same momentum, but a neutron has about 1,800 times the mass of an electron, so it moves **much more slowly**, and **slower particles push less**.

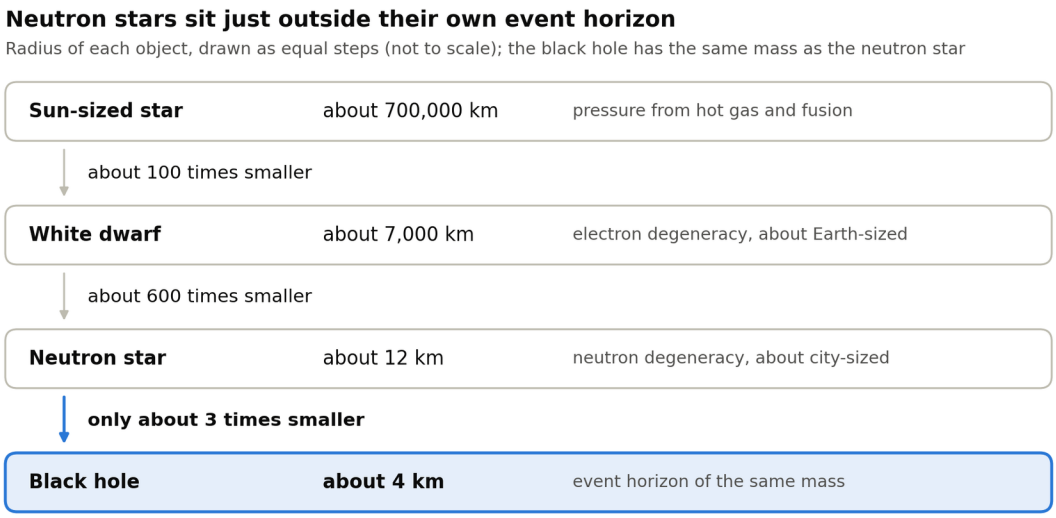


1. Compare panels 1 and 2. The crowding (Radius) is the same, yet the neutron gas pushes much less. What is different about them that causes them to push less at the same density?
2. For equal mass white dwarfs and neutron stars, the inward pull of gravity is the same. If the electrons in panel 1 are able to balance this force of gravity, what would happen to the neutrons in panel 2?
3. What needs to happen to the neutrons to balance the inward pull of gravity? Recall that higher densities result in higher speeds and therefore stronger outward pressure.
4. Compare your responses to questions 2 and 3. Will the neutron star of panel 2 eventually become stable?
5. A rough scaling says that, for the same mass, a degenerate star's radius is proportional to 1 divided by the mass of the particle providing the pressure. A white dwarf has a radius of about 7,000 km (roughly Earth-size). Divide it by 1,800 to estimate a neutron star's radius.

4.7.4 Black Holes

If a core is too heavy even for neutron degeneracy pressure, no known pressure can stop its collapse. The core keeps shrinking until the speed needed to escape from its surface reaches the speed of light. The radius where that happens is the event horizon, about 3 km for every solar mass of the black hole. It is not a hard surface. It is a one-way boundary: nothing travels faster than light, so nothing inside it can get out. Far from the hole, its gravity is the same as the original star's, so it does not suck in everything around it. Each step down the ladder is a huge shrink, except the last: a neutron star is only about 3 times larger than the horizon of a black hole with its mass.

Model A: Size Ladder



Model B: Escape Speeds

The table shows how the escape speed climbs as objects get more compact. All values are approximate.

Escape speed for compact objects

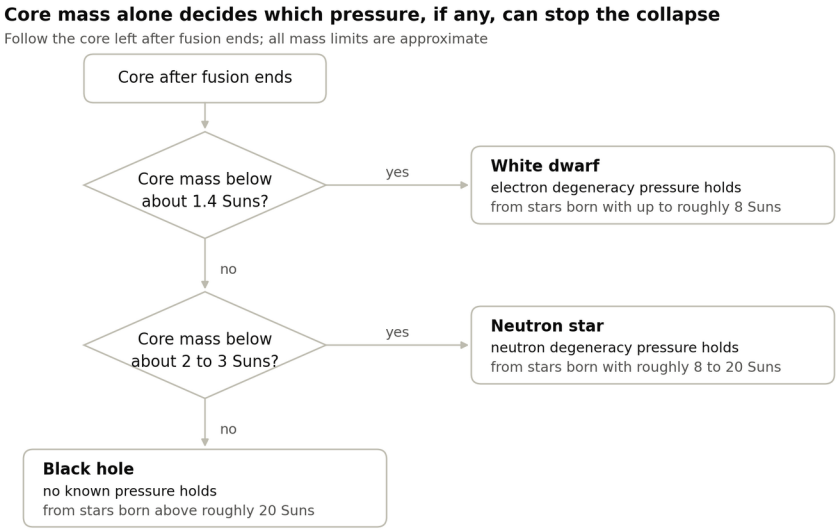
Object	Mass (Sun = 1)	Radius	Escape speed	Fraction of light speed
Earth	0.000003	6,400 km	11 km/s	0.00004
Sun	1	700,000 km	620 km/s	0.002
White dwarf	0.6	7,000 km	5,000 km/s	0.02
Neutron star	1.4	12 km	180,000 km/s	0.6
Black hole horizon	any	about 3 km per solar mass	300,000 km/s	1

1. Going down the table, what happens to the escape speed as the same kind of mass is packed into a smaller radius? How does that point toward black holes?
2. Use the horizon radius, about 3 km times the mass in Suns, to find the horizon radius of the Sun and of a 10 solar mass black hole. For Earth (0.000003 Suns), the answer is under a centimeter. What does that say about squeezing Earth into a black hole?
3. Add mass to a neutron star. What happens to the size of its horizon, and what must eventually happen to the star?
4. A friend says a black hole sucks in everything nearby like a vacuum cleaner. Use the diagram and your answer to question 3 to correct them.

4.7.5 Comparing End States

Model

Now put the ideas together. When fusion ends, what matters is the mass of the core left behind, not the whole star. Follow the diagram from the top: each limit is the point where one kind of pressure can no longer balance gravity. The boxes also list roughly how massive a star must be at birth. Those ranges are blurry, because stars lose mass and the details of the explosion matter.



Sort the cores. Use the diagram to fill in the last three columns for each core. For size, use the ladder in Part 4.

Mystery cores to classify

Core	Core mass (Suns)	Fate	Pressure that stops it (or none)	R
A	0.8			
B	1.3			
C	1.7			
D	3.5			
E	10			

1. Cores B and C differ by only 0.4 Suns. Explain why their final sizes differ by a factor of hundreds.
2. Describe, step by step, what happens to a white dwarf core that is slowly given more mass until it passes 1.4 Suns. Use the words electrons, neutrons and degeneracy.
3. Scientists say no known pressure can stop a core above about 2 to 3 Suns. What would have to be discovered to change that conclusion?

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5: GALAXIES

5.1: Sorting Galaxies by Shape
5.2: What Galaxies Tell Us About Their Stars
5.3: The Milky Way Galaxy
5.4: Dark Matter

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5.1: Sorting Galaxies by Shape

A galaxy is a huge system of billions of stars, along with gas and dust, held together by gravity. Astronomers sort galaxies into types by their shapes. Before you learn the official system, your group will invent your own.

If your instructor gives you a set of printed cards, the card numbers match the numbers on this page. The pictures are not to scale: some of these galaxies are much larger than others.

Sorting Galaxies

Model

Model 1: Nine galaxies. Each card shows one galaxy photographed by the Hubble Space Telescope.



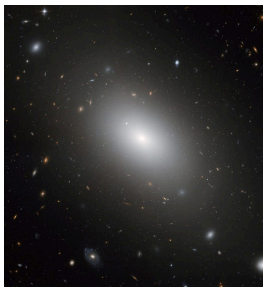
Card 1



Card 2



Card 3



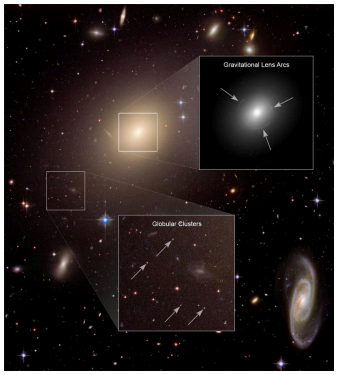
Card 4



Card 5



Card 6



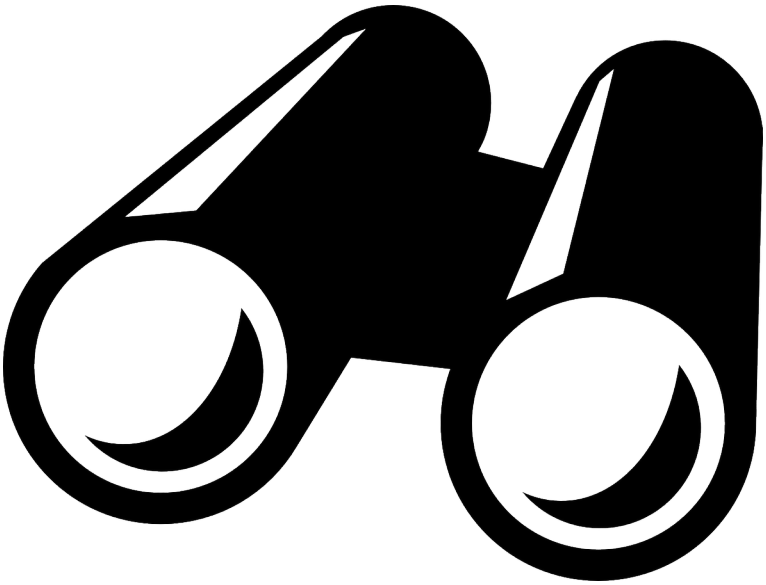
Card 7



Card 8



Card 9



Explore

1. Look at all nine cards. List at least three features that differ from one galaxy to another. For example, how round is the outline?

2. Sort the nine cards into exactly three groups. Every card must go in a group. Give each group a name and write the rule that decides which cards belong in it.

	Your name for the group	Card numbers	Rule: what do all the cards in this group share?
Group 1			
Group 2			
Group 3			

3. Compare your groups with another group's groups. Did you sort the cards the same way? Which card was hardest to place, and why?



Critical thinking & Concept Invention

Model 2: Ten more galaxies.



Card 10



Card 11



Card 12



Card 13



Card 14



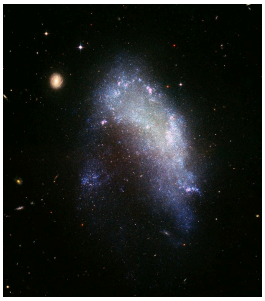
Card 15



Card 16



Card 17



Card 18



Card 19

4. Place each new card (10 to 19) into one of your three groups, if it fits. Put any card that does not fit into a "doesn't fit" pile.

Group	New cards added
Group 1	
Group 2	

Group	New cards added
Group 3	
Doesn't fit	

5. The galaxies inside one group are not identical. For each group, choose one feature that changes gradually from galaxy to galaxy. Then use all of the cards (1 to 19) in that group and put them in order from one end of the scale to the other.

Group	Feature that changes	Card numbers in order
Group 1		
Group 2		
Group 3		

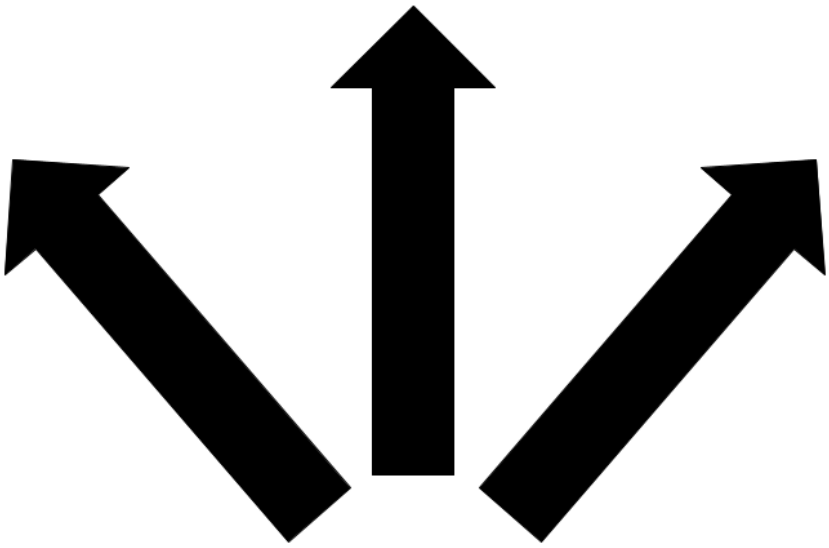
6. Look at your "doesn't fit" pile. Can you split it into smaller groups? Describe each smaller group and explain why its cards do not fit your three main groups.

Summary

7. Write a short rule your class could use to put any galaxy into one of your three main groups.

8. Complete the sentences. Galaxies in Group 1 differ mostly in _____. Galaxies in Groups 2 and 3 differ mostly in _____ and

_____.



Apply

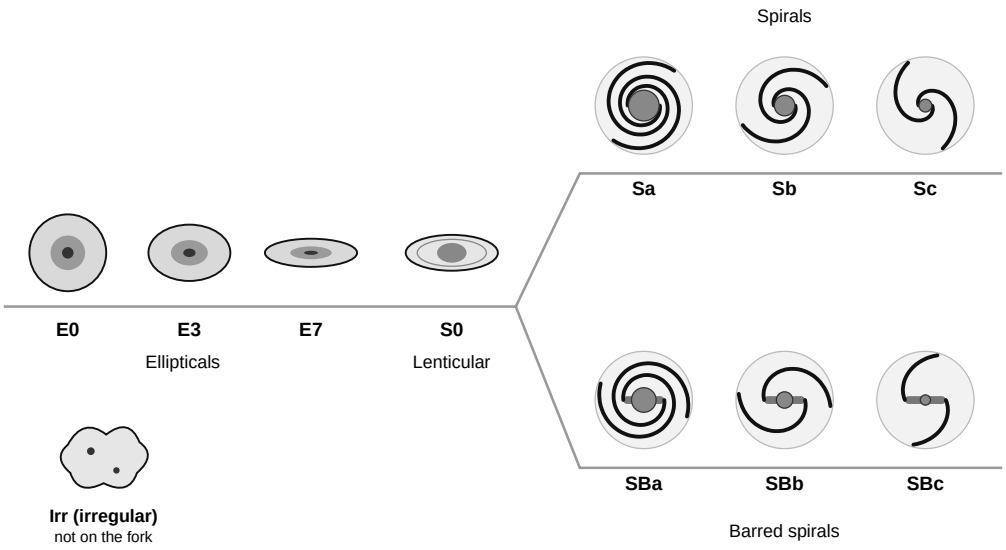
9. Our own galaxy, the Milky Way, is a barred spiral. Sketch how it might look to an astronomer in another galaxy who sees it (a) face-on and (b) edge-on.

(a) Face-on	(b) Edge-on

The Hubble Tuning Fork

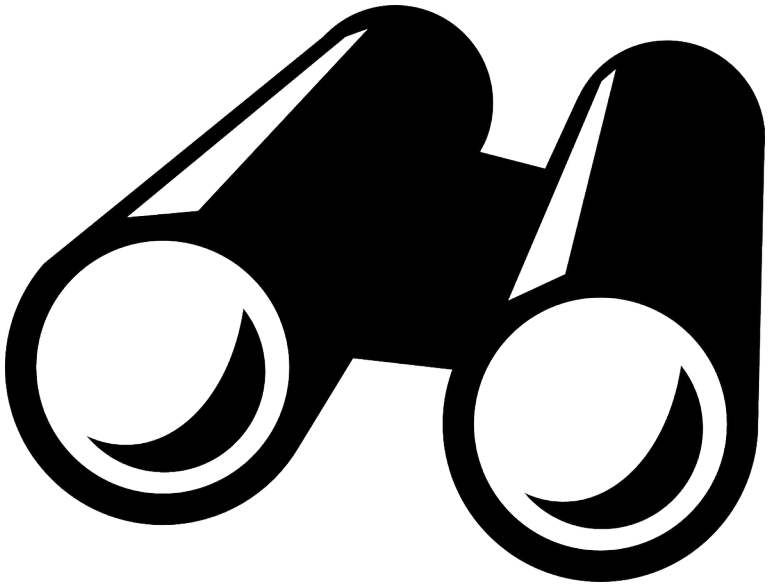
Model

Model 3: Hubble's classification. Starting in 1926, the astronomer Edwin Hubble sorted galaxies by shape. He later drew his system as a diagram called the "tuning fork" because of its shape.



Model 3. The Hubble tuning fork. The drawings show typical shapes, not real galaxies.

- **E** means elliptical. The number tells how stretched the galaxy looks. E0 looks round. E7 looks the most stretched.
- **S0** means lenticular (lens-shaped). It has a flat disk and a bright central bulge, but no spiral arms.
- **S** means spiral, and **SB** means barred spiral. The letter a, b, or c describes the arms and the central bulge. Type a has a large bulge and tightly wound arms. Type c has a small bulge and loose, open arms.
- **Irr** means irregular. These galaxies have no regular shape, so they are not on the fork.



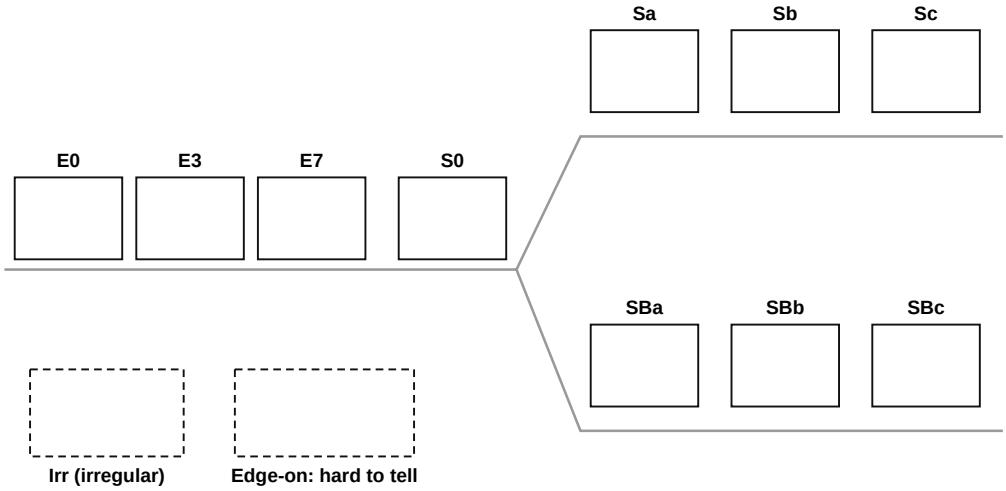
Explore

10. Match each of your three groups from Model 1 to one of Hubble's main types.

Your group name	Hubble's type (E, S, or SB)

Your group name	Hubble's type (E, S, or SB)

11. Write the number of each card (1 to 19) in the box where it fits best. Use the two dashed boxes for cards that you cannot place on the fork.



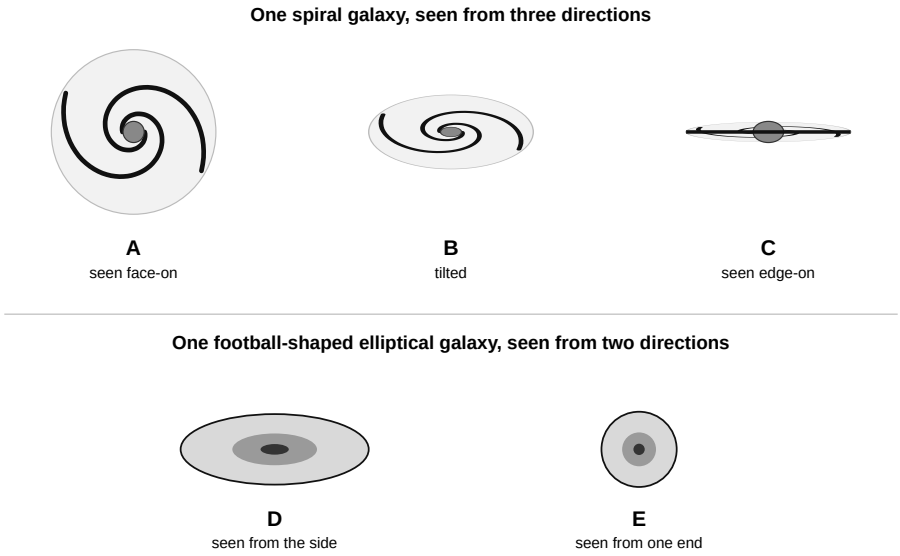
Blank tuning fork for your cards.

12. How do the scales you made in question 5 compare with Hubble's? Which of your features match Hubble's E numbers, and which match his letters a, b, and c?



Critical thinking & Concept Invention

Model 4: Viewing angle. We see each galaxy from only one direction.



Model 4. A to C: one spiral galaxy seen from three directions. D and E: one football-shaped elliptical galaxy seen from two directions.

13. Views A, B, and C show the same spiral galaxy. If you could see only view C, what Hubble type would you give it? What information is lost?

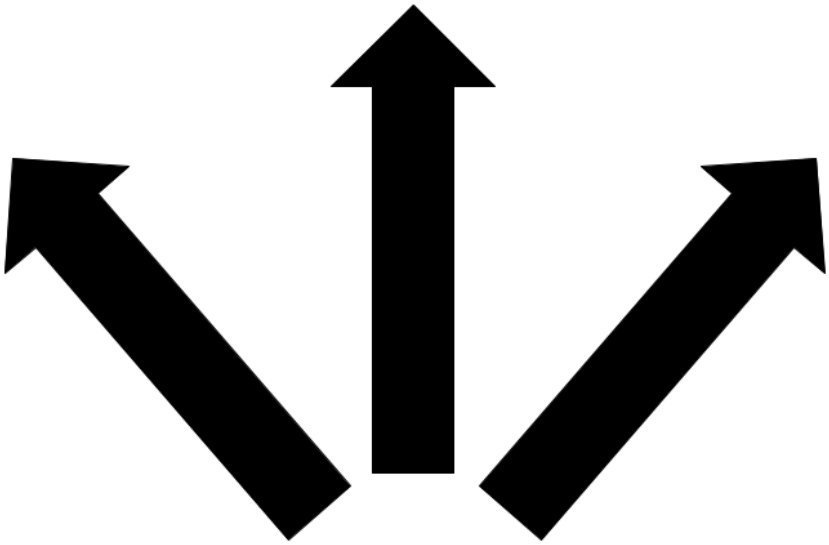
14. Views D and E show the same galaxy. What E number would an astronomer give it from view D? From view E?

15. Card 2 looks round, so it is labeled E0. Does that prove it is a round ball of stars? Explain.

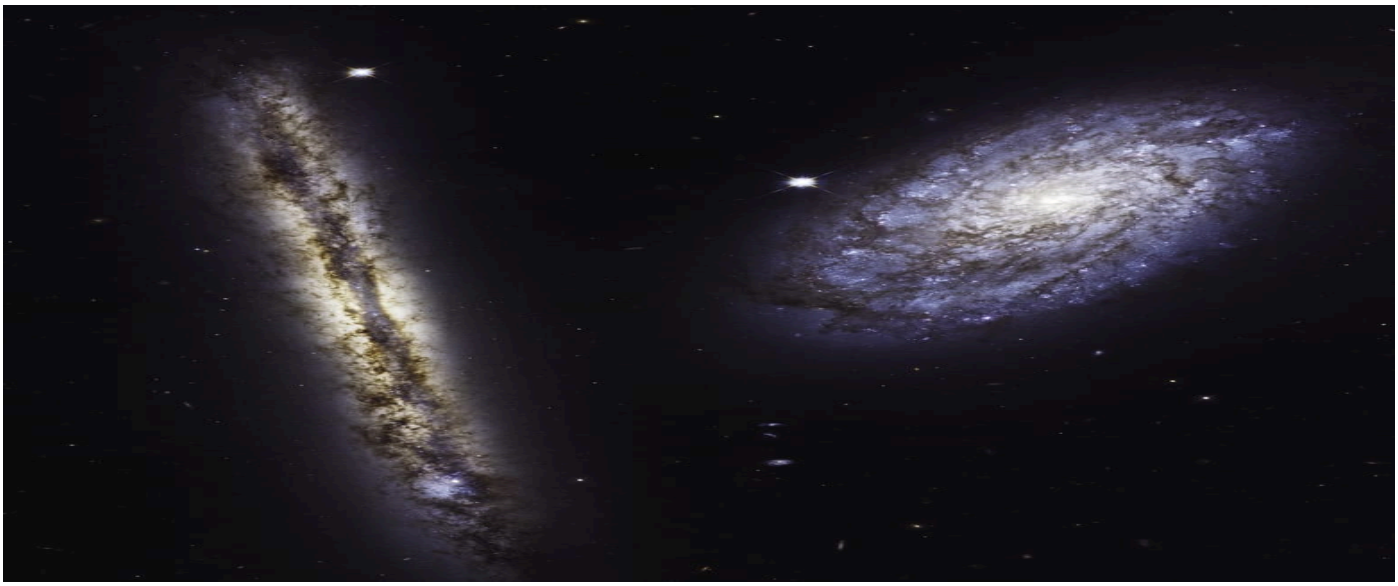
16. Cards 14 and 16 are both seen edge-on. One is a lenticular (S0) and one is a spiral. You cannot see arms in either one. Besides arms, what else could you look for to tell them apart? Invent a test.

Summary

17. Complete the sentences. Hubble's main types are elliptical (E), _____ (S0), spiral (S), _____ (SB), and _____ (Irr). The number after E describes _____. The letters a, b, and c describe _____ and _____. How a galaxy looks also depends on _____.



Apply



Two neighbors

18. Astronomers think these two neighboring galaxies are very similar spirals. Give each one a Hubble type based only on how it looks. Then explain why they look so different.

Image credits

Galaxy photos are from the Hubble Space Telescope. Diagrams are original to this workbook.

- Card 1: NGC 1300. Credit: NASA, ESA, and The Hubble Heritage Team (STScI/AURA); Acknowledgment: P. Knezek (WIYN).

Source

- Card 2: Messier 87. Credit: NASA and The Hubble Heritage Team (STScI/AURA). Source
- Card 3: Messier 74. Credit: NASA, ESA, and the Hubble Heritage (STScI/AURA)-ESA/Hubble Collaboration; Acknowledgment: R. Chandar and J. Miller. Source
- Card 4: NGC 1132. Credit: NASA, ESA, and the Hubble Heritage (STScI/AURA)-ESA/Hubble Collaboration; Acknowledgment: M. West (ESO, Chile). Source
- Card 5: NGC 1672. Credit: NASA, ESA, and The Hubble Heritage Team (STScI/AURA)-ESA/Hubble Collaboration. Source
- Card 6: Messier 101. Credit: NASA, ESA, K. Kuntz (JHU), F. Bresolin (University of Hawaii), J. Trauger (JPL), J. Mould (NOAO), Y.-H. Chu (University of Illinois, Urbana), and STScI; CFHT and NOAO ground-based data. Source
- Card 7: ESO 325-G004. Credit: NASA, ESA, and The Hubble Heritage Team (STScI/AURA); Acknowledgment: J. Blakeslee (Washington State University). Source
- Card 8: NGC 1073. Credit: NASA and ESA. Source
- Card 9: NGC 1309. Credit: NASA, ESA, The Hubble Heritage Team (STScI/AURA), and A. Riess (STScI). Source
- Card 10: Messier 81. Credit: NASA, ESA, and The Hubble Heritage Team (STScI/AURA); Acknowledgment: A. Zezas and J. Huchra (CfA). Source
- Card 11: NGC 4449. Credit: NASA, ESA, A. Aloisi (STScI/ESA), and The Hubble Heritage (STScI/AURA)-ESA/Hubble Collaboration. Source
- Card 12: Messier 59. Credit: ESA/Hubble & NASA, P. Cote (CC BY 4.0). Source
- Card 13: NGC 1015. Credit: ESA/Hubble & NASA, A. Riess (STScI/JHU) (CC BY 4.0). Source
- Card 14: NGC 5866. Credit: NASA, ESA, and The Hubble Heritage Team (STScI/AURA); Acknowledgment: W. Keel (University of Alabama). Source
- Card 15: Messier 64. Credit: NASA, CSA, ESA, F. Belfiore, J. Lee, A. Leroy, and D. Thilker; Processing: Gladys Kober. Source
- Card 16: NGC 4217. Credit: ESA/Hubble & NASA, Acknowledgement: R. Schoofs (CC BY 4.0). Source
- Card 17: NGC 3384. Credit: ESA/Hubble & NASA/B. Lehmer et al. (CC BY 4.0). Source
- Card 18: NGC 1427A. Credit: NASA, ESA, and The Hubble Heritage Team (STScI/AURA); Acknowledgment: M. Gregg. Source
- Card 19: Messier 104 (Sombrero). Credit: NASA and The Hubble Heritage Team (STScI/AURA). Source
- Two neighbors: NGC 4302 (left) and NGC 4298 (right). Credit: NASA, ESA, and M. Mutchler (STScI). Source

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5.2: What Galaxies Tell Us About Their Stars

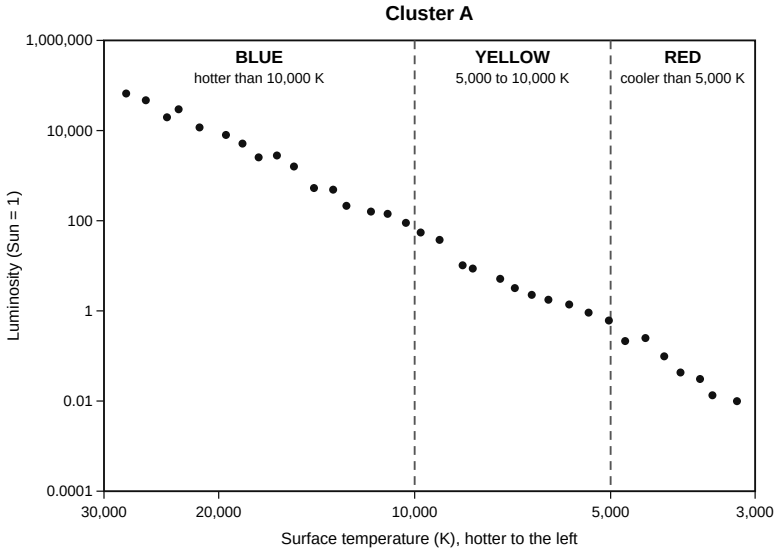
In Part 1 you sorted galaxies by shape. Now you will use the colors of their stars to find out whether each galaxy is still making new stars. The galaxy cards have the same numbers as in Part 1.

Blue Stars Are Young Stars

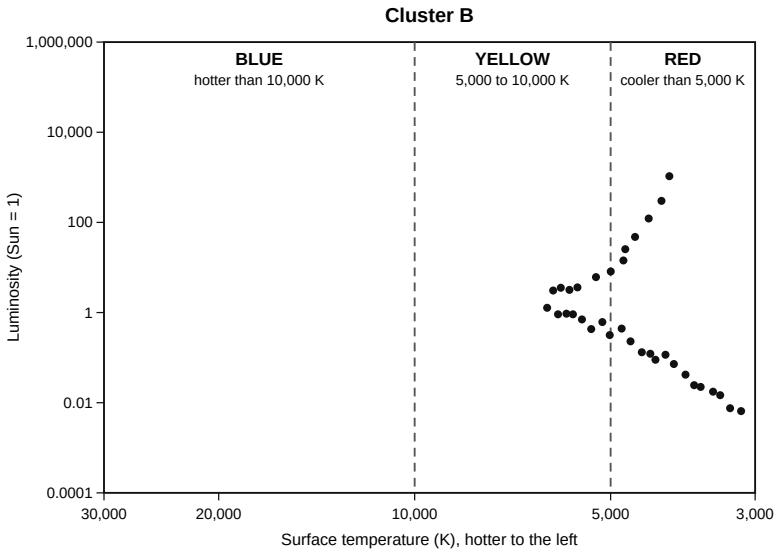
Model

Model 1: Two star clusters. All the stars in a cluster formed at about the same time. Each dot is one star.

Before you start: On both diagrams, color the band hotter than 10,000 K blue, the band from 5,000 to 10,000 K yellow, and the band cooler than 5,000 K red. Color lightly so you can still see the dots.



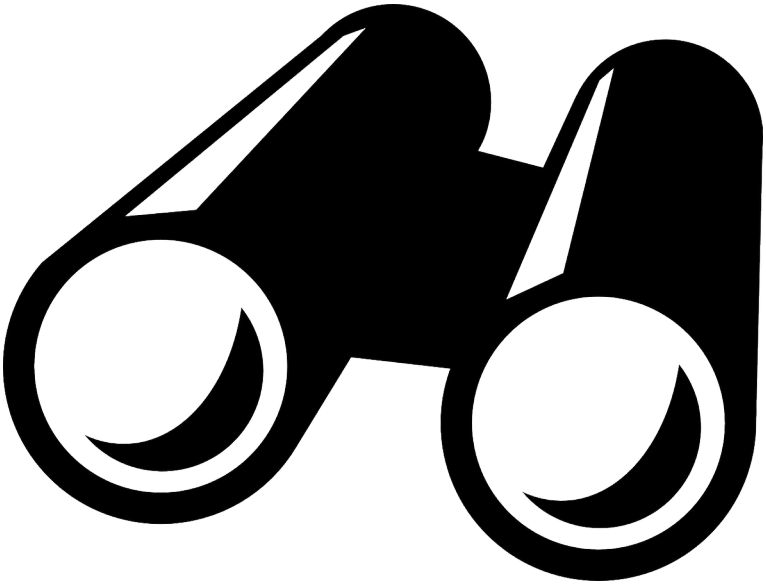
Cluster A.



Cluster B.

How long stars last on the main sequence (approximate)

Color of star	Mass compared with the Sun	Time on the main sequence
Blue (hotter than 10,000 K)	more than about 3 times	a few million to a few hundred million years
Yellow (5,000 to 10,000 K)	about 1 to 3 times	about 1 billion to 10 billion years (the Sun: about 10 billion)
Red (cooler than 5,000 K)	less than the Sun	tens of billions of years or more, longer than the universe has existed (about 14 billion years)



Explore

1. Which cluster still has main-sequence stars in the blue band? _____

2. In Cluster B, the main sequence ends at the turnoff point. About what temperature is the turnoff, and which color band is it in?

3. Use the table. What happened to the blue stars that Cluster B once had?

4. Which cluster is older? Estimate the age of each cluster.



Critical thinking & Concept Invention

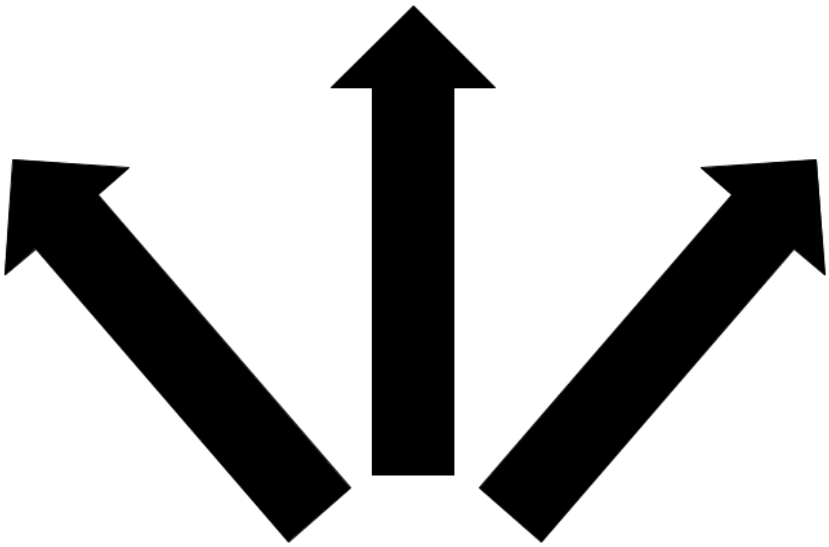
5. A classmate says Cluster A could be 5 billion years old. Use evidence from Model 1 to respond.

6. Now think about a whole galaxy instead of one cluster. Suppose part of a galaxy glows blue because it has many hot blue stars. Write a rule: what does blue light tell you about when stars formed there?

7. A galaxy shows only yellow and red light, with no blue. Does that mean it never formed any stars? Explain.

Summary

8. Complete the sentences. Blue stars are _____ massive than the Sun and live _____ lives. So blue light in a galaxy means stars _____.



Apply

9. Most large galaxies are about 10 billion years old or older. One such galaxy contains many blue stars. Are those blue stars as old as the galaxy? Explain.

Searching for Star Formation

Model

Model 2: Four galaxies up close. In these Hubble photos:

- Bright **blue** patches are clusters of young, hot stars.
- Glowing **pink or red** clouds are gas lit up by young stars. They also mark places where stars are forming.

- Smooth **yellowish** light comes mostly from older stars.

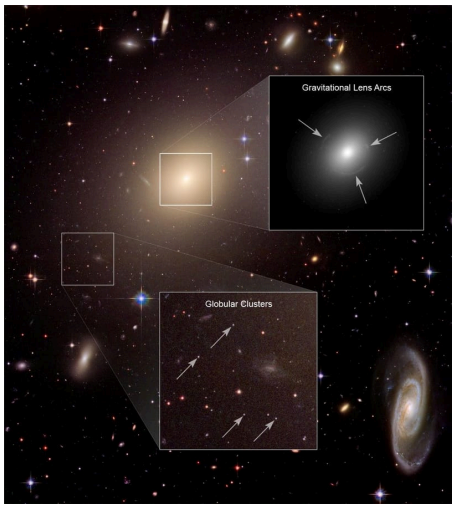
The colors are made by combining pictures taken through several filters, so they are close to, but not exactly, what your eye would see.



Card 3



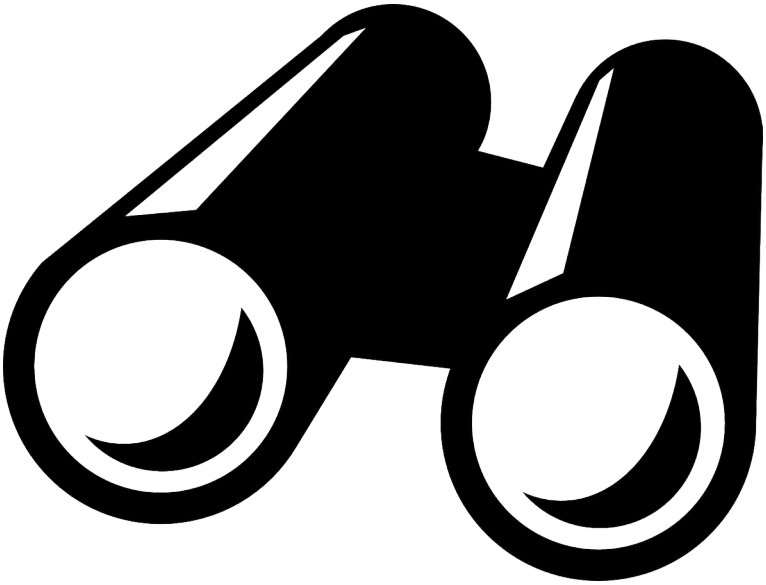
Card 1



Card 7



Card 11



Explore

10. On each of the four photos, circle every blue region you can find. Use a blue pencil if you have one.

11. Fill in the table. Use Part 1 for the Hubble type, and look back at the cards on that page for any galaxy not shown above.

Card	Hubble type	Amount of blue (none, a little, a lot)	Where is the blue? (arms, center, everywhere, nowhere)	Color of the center
3				
1				
9				
10				
7				
4				
12				
11				



Critical thinking & Concept Invention

12. Which types of galaxy have the most blue? Which have the least?

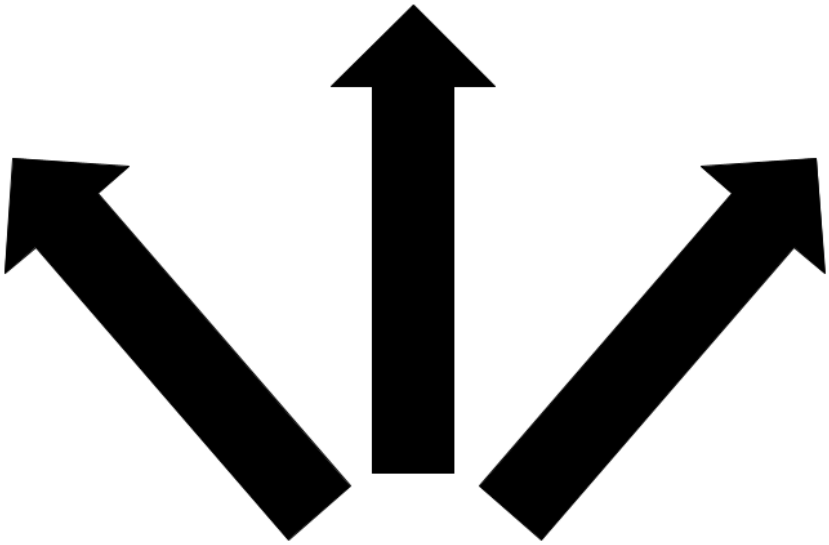
13. Inside the spiral galaxies, where is the blue, and where is the yellow? What does this tell you about the ages of the stars in the arms compared with the stars in the central bulge?

14. Compare card 10 (Hubble type a or b, large bulge) with card 3 (type c, small bulge). Which has more blue? Predict a pattern along the spiral scale from a to c.

15. Use your rule from question 6. Which of the galaxies in your table are forming stars now? Which stopped forming stars long ago?

Summary

16. Complete the sentences. Spiral, barred spiral, and irregular galaxies have _____, so they are _____. Elliptical galaxies have _____, so their stars are _____. In spirals, new stars form mainly in the _____.



Apply

17. Card 18 is an irregular galaxy. Before you look at its colors, predict whether it is forming stars. Then check the card in Part 1. Were you right?

Fuel for New Stars

Model

Model 3: Dust. Stars form inside cold clouds of gas mixed with dust. In photos, dust shows up as dark lanes or patches that block the light behind them. The thin bluish line near the center of card 2 is a jet of gas shot out from near a black hole. It is not made of stars.



Card 19



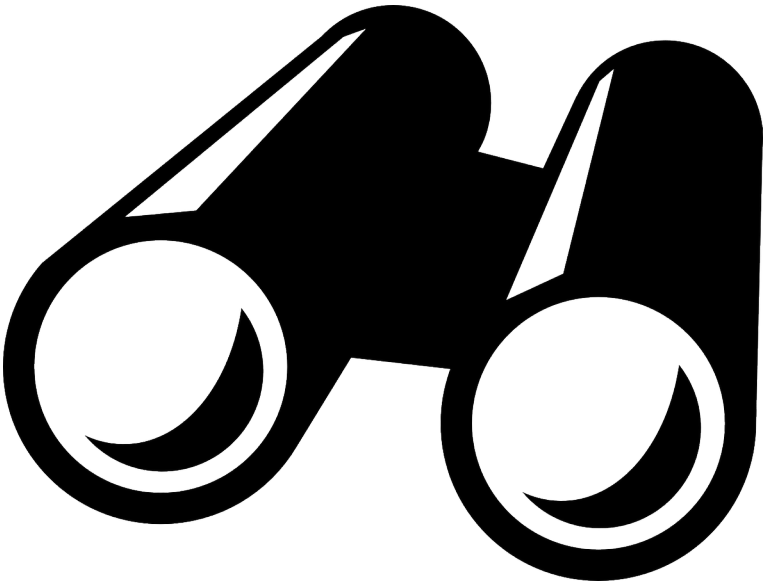
Card 16



Card 15



Card 2



Explore

18. Fill in the table.

Card	Is there dark dust? Where?	Are there blue or pink regions? Where?
19		
16		
15		
2		



Critical thinking & Concept Invention

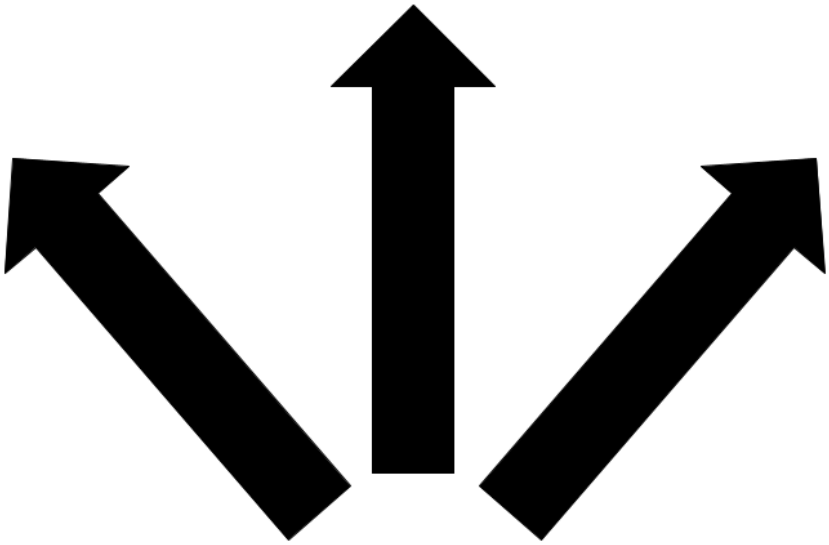
19. What do the galaxies with blue regions have that the elliptical galaxies do not have?

20. Explain why elliptical galaxies cannot form many new stars.

21. Card 19 has a lot of dust but only a little blue. What does this suggest about the connection between dust and star formation?

Summary

22. Complete the chain. Cold gas and dust, then _____, then _____, then after a few million years _____, unless _____.



Apply

23. Card 14 is a lenticular (S0) galaxy with one thin dust lane. Predict whether it has a lot of star formation, a little, or none. What would you look for in the photo to check?

When Galaxies Collide

Model

Model 4: Galaxies meeting. These four photos show galaxies at different stages of a collision. They are not in order.



Image P



Image Q

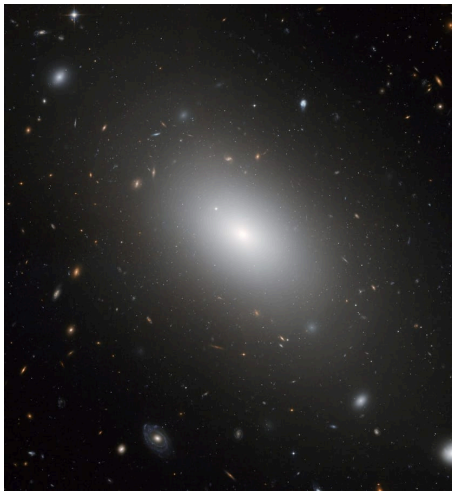
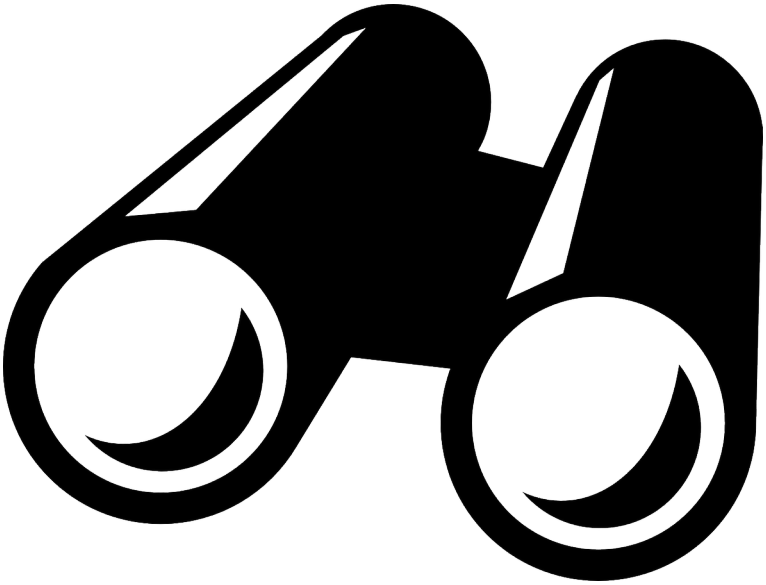


Image R



Image S



Explore

24. Put the four images in order from the earliest stage of a collision to the latest. Explain the clues you used.

25. Which images show the most blue? Which show the least?

26. What happens to the shapes of the spiral disks as a collision goes on?



Critical thinking & Concept Invention

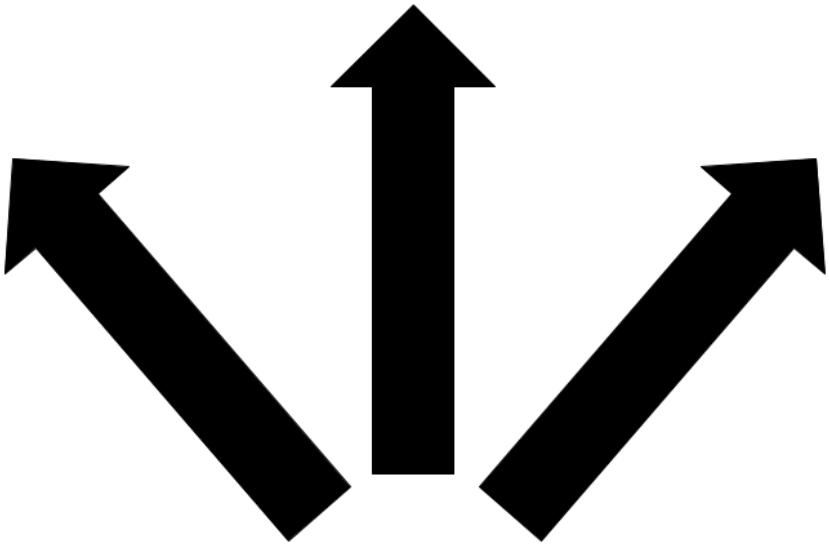
27. When galaxies collide, their gas clouds are squeezed together. Use your observations to explain why colliding galaxies have so much blue.

28. Astronomers expect that in a few billion years, the galaxy in image P will look like an ordinary elliptical galaxy. Use the star lifetimes from Model 1 to explain why its blue regions will disappear.

29. Elliptical galaxies contain only old stars and almost no gas. Could an elliptical galaxy turn into a spiral galaxy on its own? What would it need? Use evidence from this activity.

Summary

30. Complete the sentences. When two spiral galaxies collide, their gas is _____ and many _____ stars form. Later the gas is _____, the blue stars _____, and the merged galaxy can look like an _____ galaxy.



Apply

Classify like a citizen scientist. In the online project Galaxy Zoo, volunteers classify galaxy photos to help astronomers. Try it with two new images.



Image T



Image U

31. Fill in the table. Image T contains two galaxies.

Galaxy	Hubble type	Amount of blue	Forming many stars now? (yes or no)
Image T, large galaxy			

Galaxy	Hubble type	Amount of blue	Forming many stars now? (yes or no)
Image T, small galaxy			
Image U			

32. The galaxy in image U has a spiral shape but much less blue than most spirals. It lives in a crowded cluster of galaxies. Suggest what might have happened to it.

Image credits

Galaxy photos are from the Hubble Space Telescope. Diagrams are original to this workbook.

- Card 1: NGC 1300. Credit: NASA, ESA, and The Hubble Heritage Team (STScI/AURA); Acknowledgment: P. Knezek (WIYN). Source
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- Card 3: Messier 74. Credit: NASA, ESA, and the Hubble Heritage (STScI/AURA)-ESA/Hubble Collaboration; Acknowledgment: R. Chandar and J. Miller. Source
- Card 7: ESO 325-G004. Credit: NASA, ESA, and The Hubble Heritage Team (STScI/AURA); Acknowledgment: J. Blakeslee (Washington State University). Source
- Card 11: NGC 4449. Credit: NASA, ESA, A. Aloisi (STScI/ESA), and The Hubble Heritage (STScI/AURA)-ESA/Hubble Collaboration. Source
- Card 15: Messier 64. Credit: NASA, CSA, ESA, F. Belfiore, J. Lee, A. Leroy, and D. Thilker; Processing: Gladys Kober. Source
- Card 16: NGC 4217. Credit: ESA/Hubble & NASA, Acknowledgement: R. Schoofs (CC BY 4.0). Source
- Card 19: Messier 104 (Sombrero). Credit: NASA and The Hubble Heritage Team (STScI/AURA). Source
- Image P: NGC 7252 (center). Credit: NASA & ESA, Acknowledgements: Judy Schmidt (CC BY 4.0). Source
- Image Q: The Mice (NGC 4676). Credit: NASA, H. Ford (JHU), G. Illingworth (UCSC/LO), M. Clampin (STScI), G. Hartig (STScI), the ACS Science Team, and ESA. Source
- Image R: NGC 1132 (same galaxy as card 4). Credit: NASA, ESA, and the Hubble Heritage (STScI/AURA)-ESA/Hubble Collaboration; Acknowledgment: M. West (ESO, Chile). Source
- Image S: The Antennae (NGC 4038 and NGC 4039). Credit: NASA, ESA, and the Hubble Heritage Team (STScI/AURA)-ESA/Hubble Collaboration; Acknowledgment: B. Whitmore (STScI). Source
- Image T: Arp 116: Messier 60 (large) and NGC 4647 (small). Credit: NASA, ESA, and the Hubble Heritage (STScI/AURA)-ESA/Hubble Collaboration. Source
- Image U: NGC 4921. Credit: NASA, ESA, and K. Cook (Lawrence Livermore National Laboratory). Source

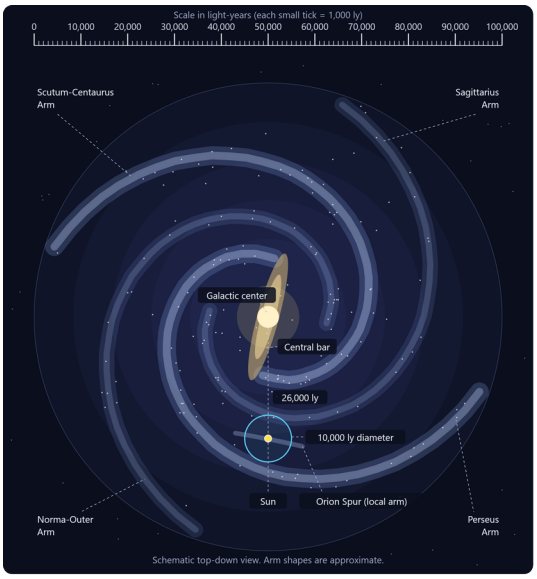
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5.3: The Milky Way Galaxy

5.2 The Milky Way Galaxy

Model

The diagram below is a representation of the Milky Way Galaxy. The ruler at the top measures distance in light years with each small tick of the ruler representing 1,000 light years. The sun is shown in its position in the galaxy. The learning cycles on this page all involve interacting with this galaxy model.



5.2.1 Position of the Sun

1. Describe the position of the Sun (edge, center, etc) within the Milky Way Galaxy
2. What is the approximate distance from the Sun to the center of the Milky Way?

5.2.2 Positions of Bright Stars

Model

The table below identifies the brightest stars in the night sky. **Note:** Depending on your latitude, you might not be able to see all of these stars.

The 10 Brightest Stars in the Night Sky

Star Name	Apparent Magnitude	Absolute Magnitude	Distance (light-years)
Sirius	-1.46	+1.45	8.6
Canopus	-0.74	-5.5	310
Alpha Centauri	-0.27	+4.1	4.37
Arcturus	-0.05	-0.3	36.7
Vega	+0.03	+0.6	25

Star Name	Apparent Magnitude	Absolute Magnitude	Distance (light-years)
Capella	+0.08	+0.1	43
Rigel	+0.13	-6.4	860
Procyon	+0.38	+2.7	11.4
Achernar	+0.46	-2.6	140
Betelgeuse	+0.50	-5.1	427

1. Based on these distances, are these stars inside the Milky Way Galaxy or are they part of another galaxy? Explain your thinking.
2. Are these stars inside or outside of the circle that is drawn on the diagram around the sun?
3. Draw a circle around the sun (as best you can) that is just big enough to include all of these stars (but no bigger). Discuss what that means for the radius and/or diameter of this circle before you draw it.
4. Would you consider these nearby stars or far away stars? Explain your thinking.

5.2.3 Positions of Dim Stars

Model

The stars below are visible to the unaided eye, but are quite dim. The values are approximates/averages because exact data is unknown and different methods establish different upper and lower limits on distance.

Distant Stars Visible to the Unaided Eye (Approximate Values)

Star Name	Apparent Magnitude	Absolute Magnitude	Distance (light-years)
Deneb	+1.25	-7	1,600–2,600
Mu Cephei	+4.1 to +5.0	Uncertain	Highly uncertain; several thousand
Nu Cephei	+4.3	-6	5,100
Alpha Camelopardalis	+4.3	-7.1	2,600
Eta Carinae	+4 to +6	Highly uncertain	7,500
Rho Cassiopeiae	+4.1 to +6.2	-9.5	~ 9,200
Chi Carinae	+3.6	-2.25	450
V810 Centauri (Binary)	+5.0	−8.4 (A); −5.1 (B)	~ 7,600
Phi Cassiopeiae	+5.0	-7	15,000
V509 Cassiopeiae	+4.6 to +6.1	-8.6	~ 11,000

1. Are these stars closer or farther from the Sun than the bright stars from the previous table? Explain why your answer makes sense.
2. Based on these distances, are these stars inside the Milky Way Galaxy or are they part of another galaxy? Explain your thinking.
3. Are these stars inside or outside of the circle that is drawn on the diagram around the sun? If any are inside the circle, highlight them on the table.
4. Draw a circle around the sun (as best you can) that is just big enough to include all of these stars (but no bigger). Discuss what that means for the radius and/or diameter of this circle before you draw it.
5. Would you consider these nearby stars or far away stars? Explain your thinking.
6. **Summarize**: When we look at individual stars in the night sky, do we see most of the stars in our galaxy or a small amount? Estimate a fraction or percentage. Explain why this makes sense.

5.2.4 Messier Objects

Model

The table below lists **Messier Objects**, which include star clusters, nebulae, galaxies, and other "fuzzy" objects that are more than just single stars. This is not a complete list.

The Five Closest and Five Farthest Messier Objects

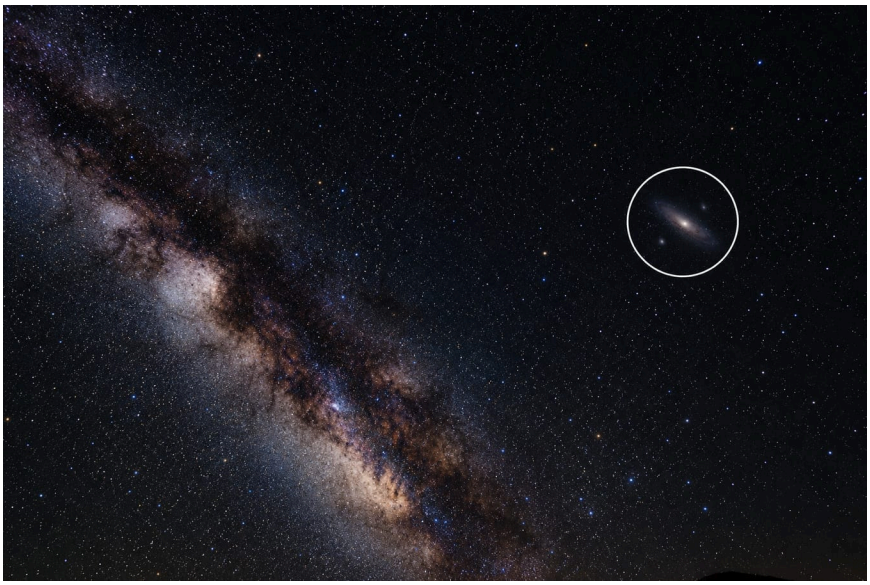
Messier Object	Apparent Magnitude	Absolute Magnitude	Diameter (light-years)	Distance (light-years)
Five Closest Objects				
M45 — Pleiades	+1.6	-4.1	13	445
M44 — Beehive Cluster	+3.1	-3.1	25	577
M39 — Open Cluster	+4.6	-2.3	7	800
M7 — Ptolemy Cluster	+3.3	-4.1	23	980
M6 — Butterfly Cluster	+4.2	-4.3	9	1,600
Five Farthest Objects				
M109 — Barred Spiral Galaxy	+10.6	-21.4	150,000	83,500,000
M91 — Barred Spiral Galaxy	+10.2	-21.2	100,000	63,000,000
M98 — Spiral Galaxy	+10.1	-21.0	160,000	55,000,000
M100 — Spiral Galaxy	+9.3	-21.8	107,000	55,000,000
M102 — Lenticular Galaxy	+10.7	-20.1	86,000	47,000,000

1. Highlight any of the Messier Objects that are within the circle around the sun in the Galaxy Model.
2. What type of object (look at the names) are the near Messier Objects?
3. Why type of object are the far Messier Objects?
4. Examine the **Diameter Column** in the table:
    1. Which objects (if any) would a small dot if drawn to scale on the Galaxy model?
    2. Which objects (if any) would a circle about the size of the one around the Sun if drawn to scale on the Galaxy model?
    3. Which objects (if any) would a circle that is much larger than the one around the Sun if drawn to scale on the Galaxy model?
5. Are any of these objects far enough away that they would be outside of the Milky Way Galaxy? If so, identify which ones and explain why that makes sense.

5.2.5 Looking at Galaxies

Model

The image below is a simulated but semi-realistic view of the night sky. The galaxy in the circle has been enlarged a bit to make it more visible (comparative scales can be tricky in astronomy images).



1. The individual stars are all brighter than the dimmest stars from the earlier tables. Are they inside our galaxy or outside of our galaxy? Are the close to the sun or far from the sun?
2. What do you think the object in the circle represents? Is it in our galaxy or outside of our galaxy? Explain your thinking.
3. What do you think the diagonal line object represents? Is it in our galaxy or outside of our galaxy? Explain your thinking.

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5.4: Dark Matter

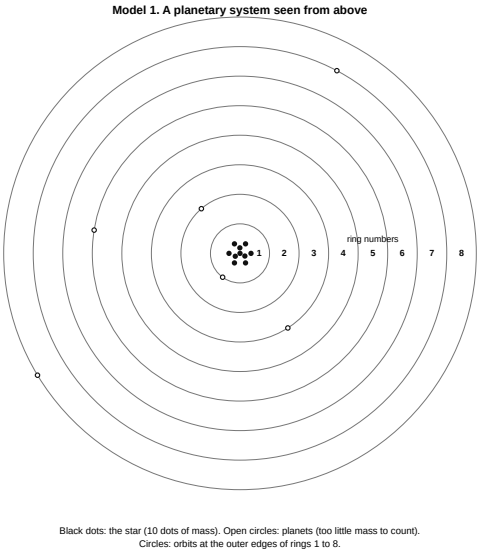
A **rotation curve** is a graph of how fast things orbit at different distances from the center of a system. In this activity you will predict the rotation curve of a galaxy, compare your prediction with real measurements, and figure out what is missing.

How to draw each graph: Every graph in this activity starts blank. First sketch the curve from the previous graph in pencil. Then use a colored pencil to draw only the parts that change. You do not need numbers. Just show where the speed is higher or lower.

What Sets an Orbital Speed?

Model

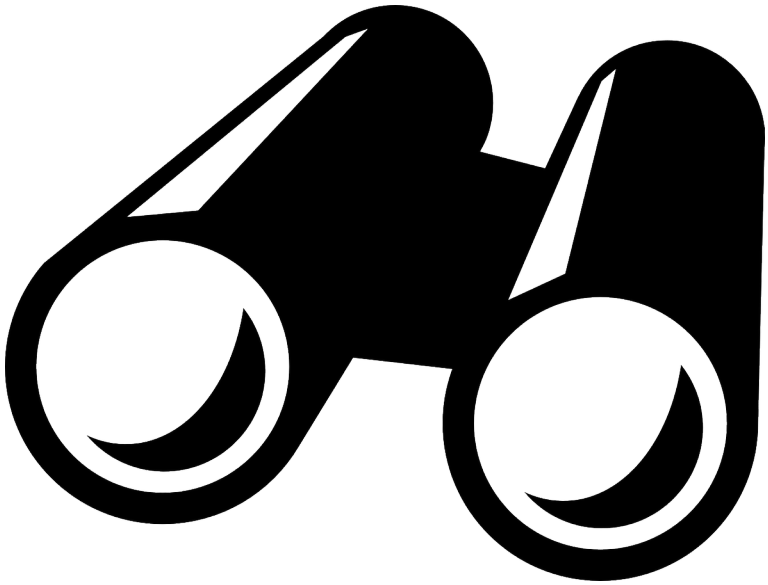
Model 1: A planetary system. Almost all of the mass is in the star at the center. Each black dot stands for the same amount of mass.



Model 1. A planetary system seen from above.

Orbital speeds of the planets in our solar system

Planet	Mercury	Venus	Earth	Mars	Jupiter	Saturn	Uranus	Neptune
Orbital speed (km/s)	47	35	30	24	13	10	7	5



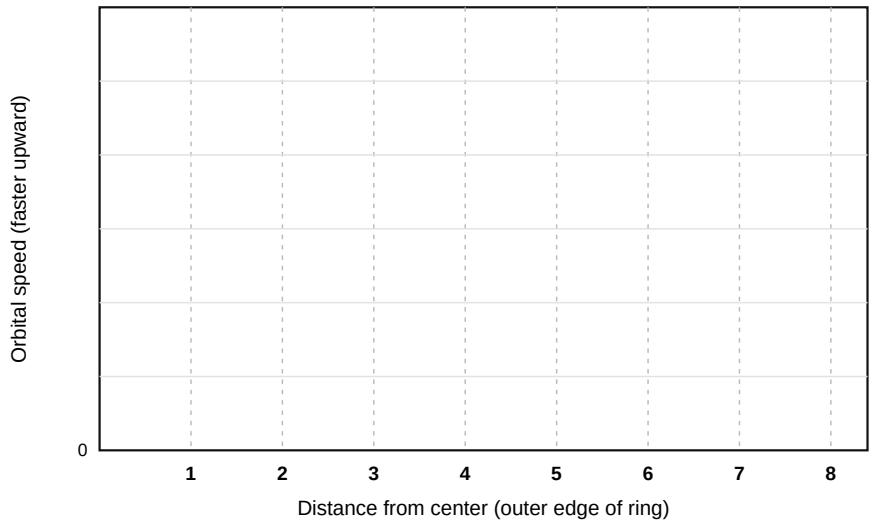
Explore

1. The planets in the table are listed from closest to the Sun to farthest. How does orbital speed change as distance from the Sun increases?

2. Count the dots in Model 1. Count the star's dots as part of ring 1. In the second row, write how many dots are inside an orbit at the outer edge of each ring.

	Ring 1	Ring 2	Ring 3	Ring 4	Ring 5	Ring 6	Ring 7	Ring 8
Dots in this ring								
Dots inside the orbit								

3. **Graph 1.** Sketch the rotation curve for Model 1 in pencil: the orbital speed at the outer edge of each ring.



Graph 1. Model 1.

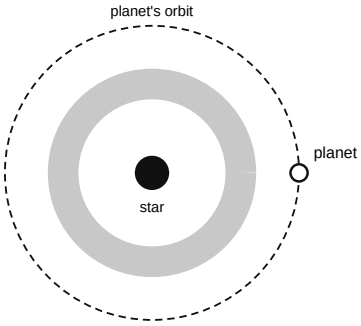
4. Every planet in Model 1 has the same mass inside its orbit. So why do the farther planets move more slowly?



Critical thinking & Concept Invention

Model 2: Extra mass in a shell. Suppose some extra mass is spread evenly in a thin, hollow shell around the star. Seen from above, the shell looks like a ring. The planet's orbit stays the same size.

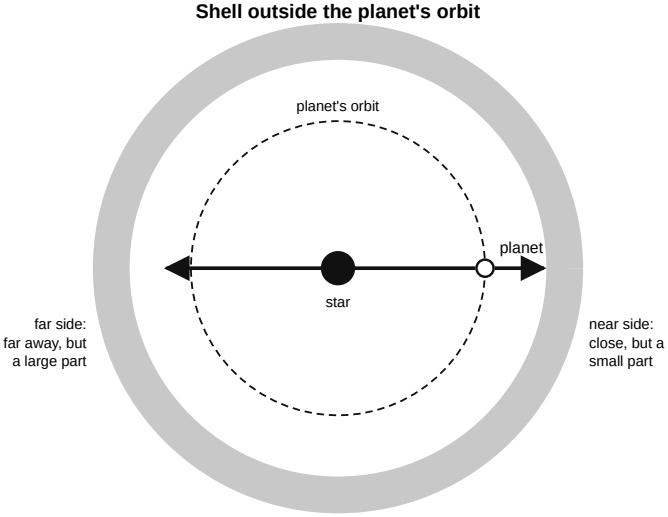
Shell inside the planet's orbit



Gray band: a thin hollow shell of extra mass around the star (seen from above).

Model 2A. The shell is inside the planet's orbit.

Shell outside the planet's orbit



Gray band: a thin hollow shell of extra mass around the star (seen from above).

Model 2B. The shell is outside the planet's orbit.

5. In Model 2A, the shell and the star both pull the planet toward the center. Compared with having no shell, should the planet move faster or slower to stay in the same orbit? Explain using question 4.

6. In Model 2B, the planet is inside the shell. The near side of the shell is close but is only a small part of the shell. The far side is far away but is a much larger part. Do the pulls from the near side and the far side add up, or do they cancel? Explain.

7. So does the shell in Model 2B change the planet's orbital speed?

8. Write a rule in your own words: which mass affects a planet's orbital speed, and which mass does not?

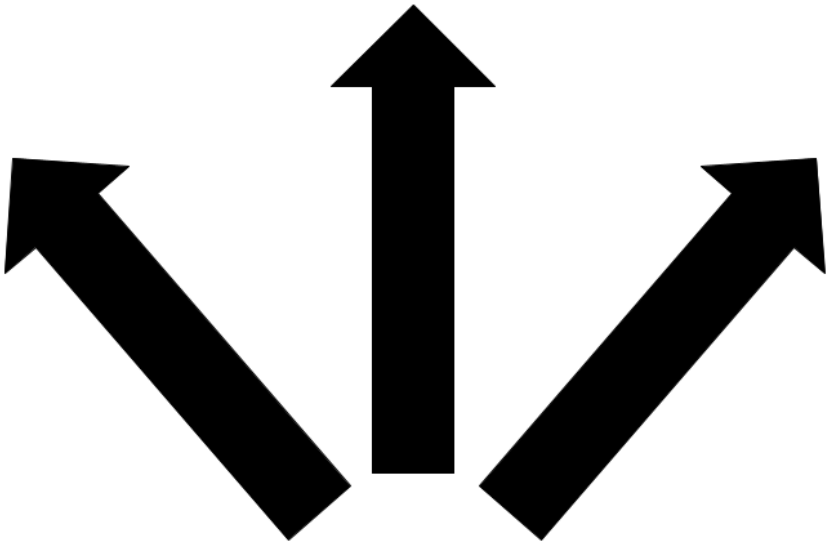
Summary

The rule for this activity

- The orbital speed at any distance depends only on the mass **inside** that orbit.
- More mass inside means a **faster** orbit.
- The same mass inside, but farther away, means a **slower** orbit.
- Mass outside the orbit does not change the speed.

9. Use the rule. Which of these changes would change Earth's orbital speed? For each one, write faster, slower, or no change.

Change	Earth's speed
(a) A shell of dust appears outside Earth's orbit.	
(b) A shell of dust appears between Venus's orbit and Earth's orbit.	
(c) The Sun's mass doubles.	



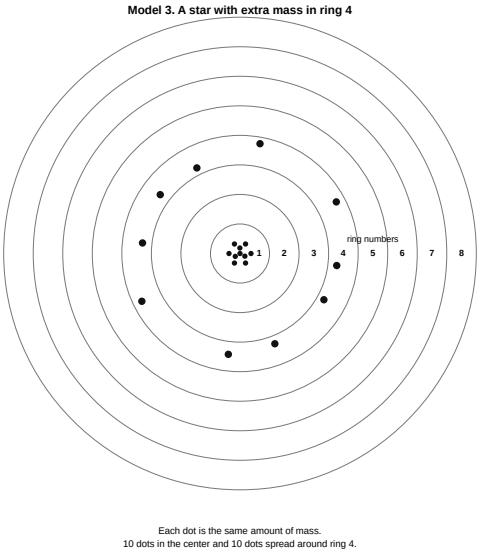
Apply

10. The asteroid belt is a wide band of rocks between the orbits of Mars and Jupiter. Does its mass affect Mars's orbital speed? Does it affect Jupiter's? (The asteroids have very little mass, so any effect is tiny.)

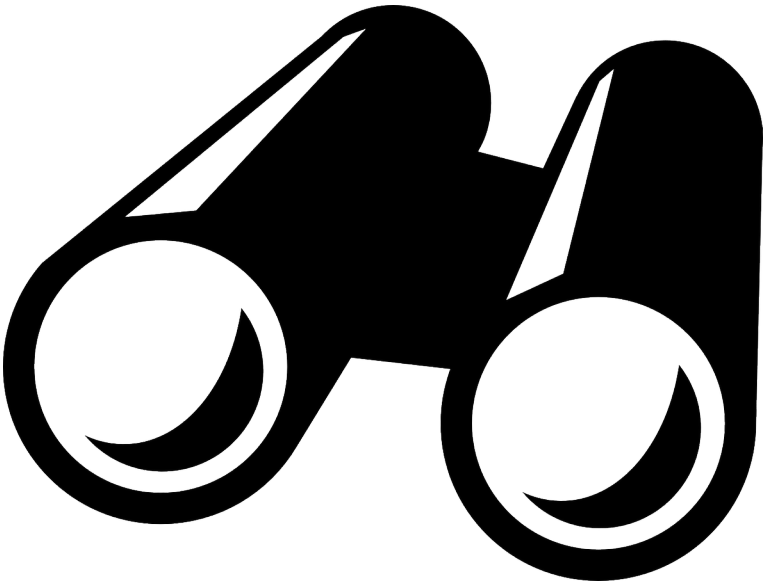
Adding Mass in a Ring

Model

Model 3: Extra mass in ring 4. This is the same star as in Model 1, plus 10 more dots of mass spread around ring 4.



Model 3. A star with extra mass in ring 4.



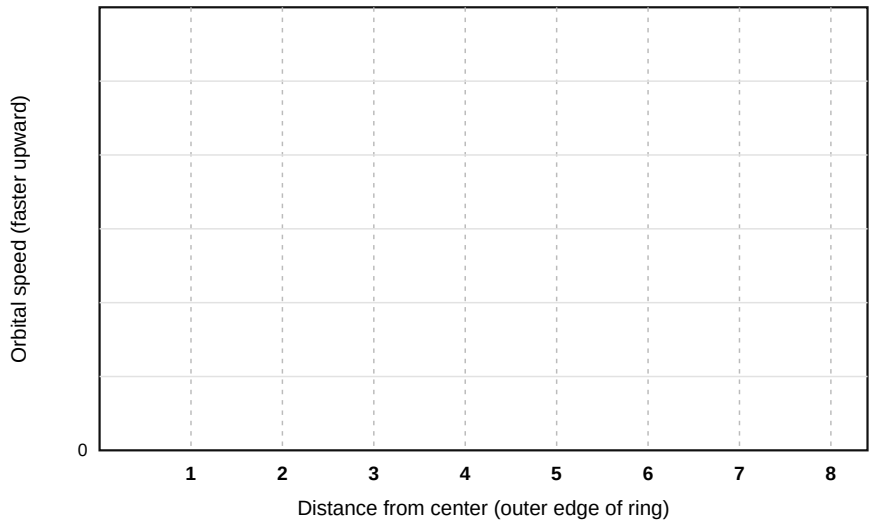
Explore

11. Fill in the counts for Model 3.

	Ring 1	Ring 2	Ring 3	Ring 4	Ring 5	Ring 6	Ring 7	Ring 8
Dots in this ring								
Dots inside the orbit								

12. Compare with your table from question 2. For which rings is the mass inside the orbit the same as in Model 1? For which rings is it different?

13. **Graph 2.** Sketch your Graph 1 curve in pencil. Then use a colored pencil to show how the curve changes for Model 3.



Graph 2. Model 3.



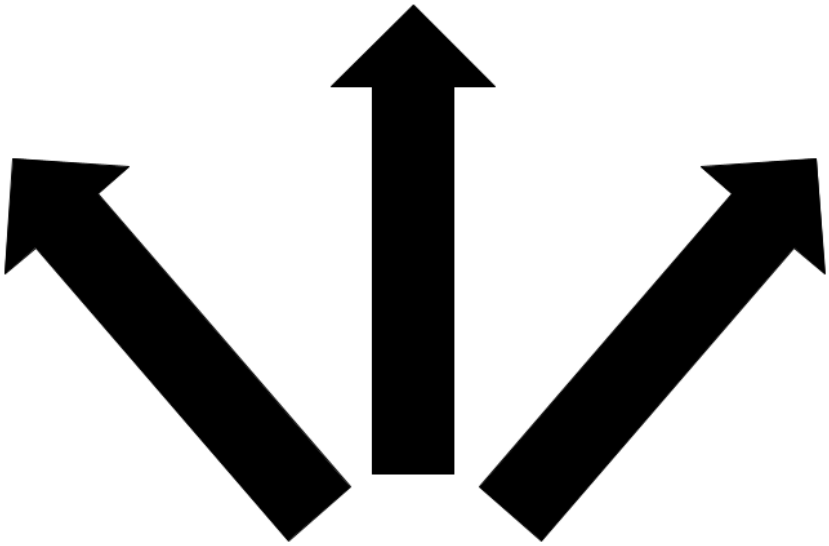
Critical thinking & Concept Invention

14. Why does the curve jump at ring 4, instead of rising gradually starting at ring 1?

15. Suppose the 10 extra dots were spread out instead: 2 dots in each of rings 4, 5, 6, 7, and 8. Describe how the curve past ring 3 would be different from Graph 2.

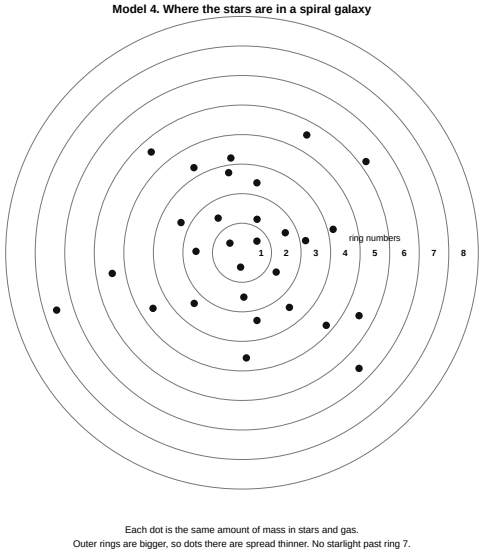
Summary

16. Complete the sentences. Adding mass in one ring changes the speed of orbits _____ that ring, but not orbits _____ it. Spreading mass farther out makes the speed _____.



Apply

Model 4: A spiral galaxy. In a galaxy, the mass is not all in the center. Astronomers can see where the stars and gas are from their light. Model 4 shows where they are in a typical spiral galaxy.

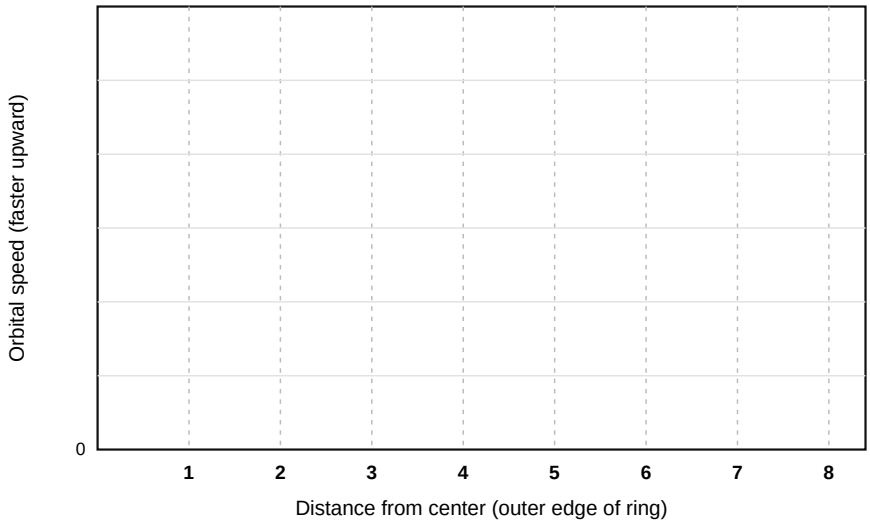


Model 4. Where the stars and gas are in a spiral galaxy.

17. Fill in the counts for Model 4.

	Ring 1	Ring 2	Ring 3	Ring 4	Ring 5	Ring 6	Ring 7	Ring 8
Dots in this ring								
Dots inside the orbit								

18. **Graph 3.** Sketch your Graph 2 curve in pencil for comparison. Then use a colored pencil to draw the rotation curve you predict for Model 4. Hint: near the center, the mass inside grows quickly from ring to ring. Far out, it hardly grows at all.



Graph 3. Your prediction for Model 4.

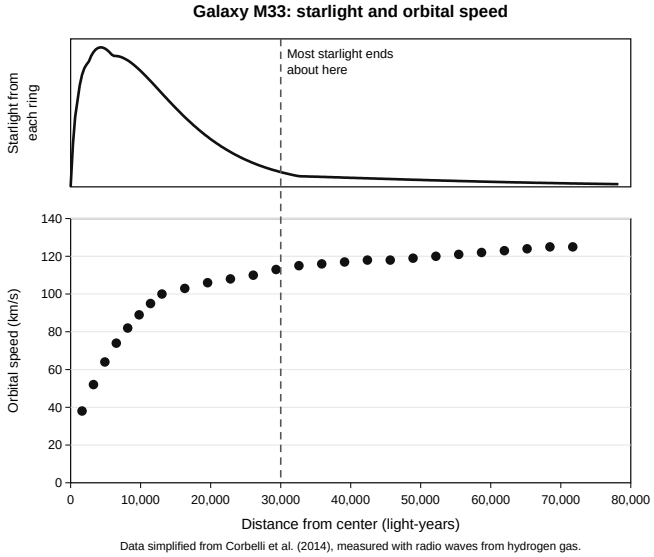
A Real Galaxy

Model

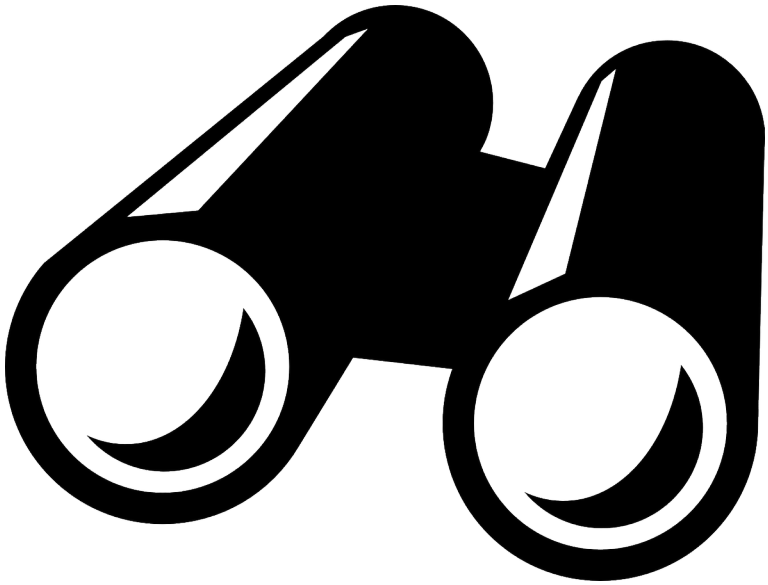
Model 5: Galaxy M33. M33, the Triangulum Galaxy, is a nearby spiral galaxy about 3 million light-years away. The photo shows its inner part. Its hydrogen gas reaches much farther out than its stars. Astronomers measure how fast the gas orbits by using the Doppler shift of radio waves from hydrogen.



The inner part of M33, photographed by the Hubble Space Telescope.



Model 5. Top: how much starlight comes from each distance. Bottom: measured orbital speed.

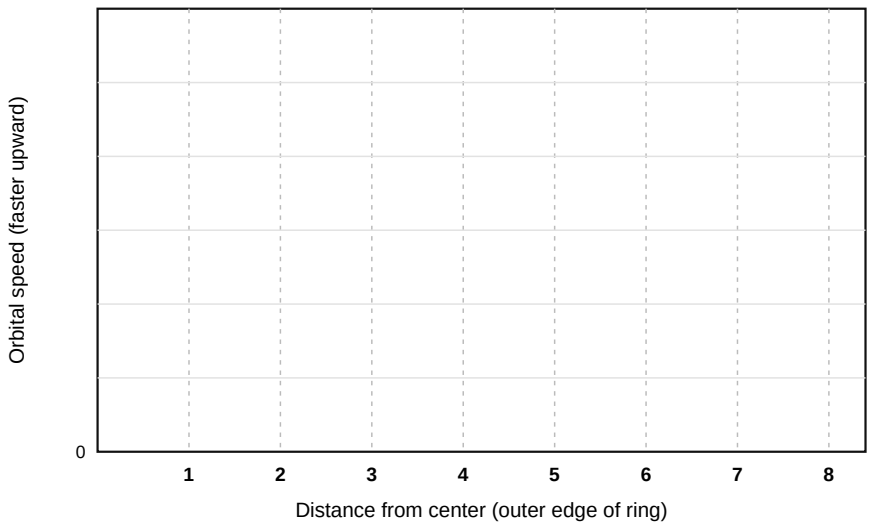


Explore

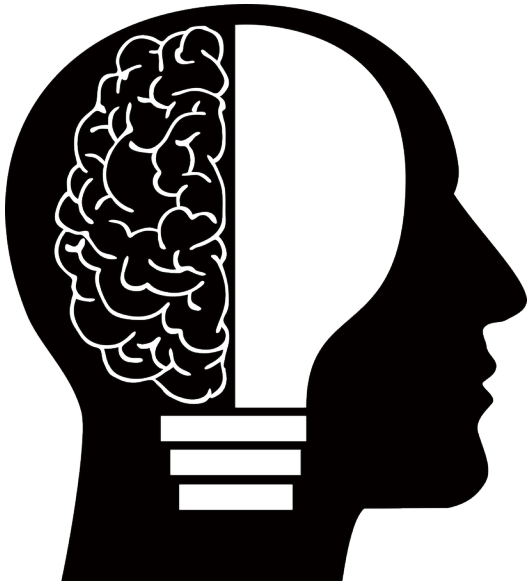
19. Look at the top graph. Where does most of M33's starlight come from? About how far out does the starlight mostly end?

20. Look at the bottom graph. Describe the measured speed close to the center and far from the center.

21. **Graph 4.** Sketch your Model 4 prediction (Graph 3) in pencil. Then use a colored pencil to sketch the shape of M33's real curve. Line it up so that the place where M33's starlight ends is at ring 7. Where do the two curves agree, and where do they disagree?



Graph 4. Your prediction and M33's real curve.



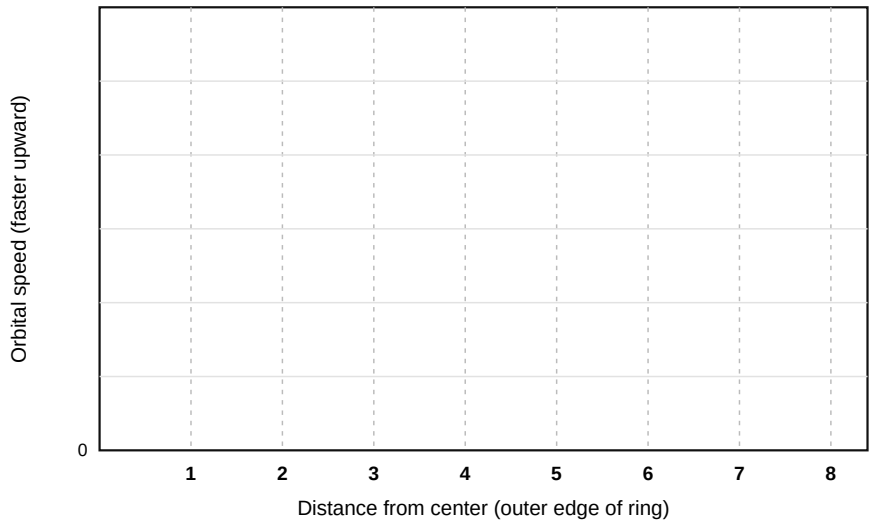
Critical thinking & Concept Invention

22. Use the rule. Far from M33's center, the distance keeps growing but the speed does not fall. What must be true about the mass inside the orbit as you go farther out?

23. Go back to Model 4. Using a colored pencil, add dots to the rings wherever they are needed so that the curve stays flat all the way to ring 8 instead of falling. Then fill in the table.

	Ring 1	Ring 2	Ring 3	Ring 4	Ring 5	Ring 6	Ring 7	Ring 8
Dots of stars and gas (Model 4)								
Dots you added								
New total inside the orbit								

24. **Graph 5.** Sketch your Model 4 prediction (Graph 3) in pencil. Then use a colored pencil to draw the curve with your added dots.



Graph 5. Model 4 with your added dots.

25. Describe the pattern of the dots you added. Where are they, and how many are in each outer ring?

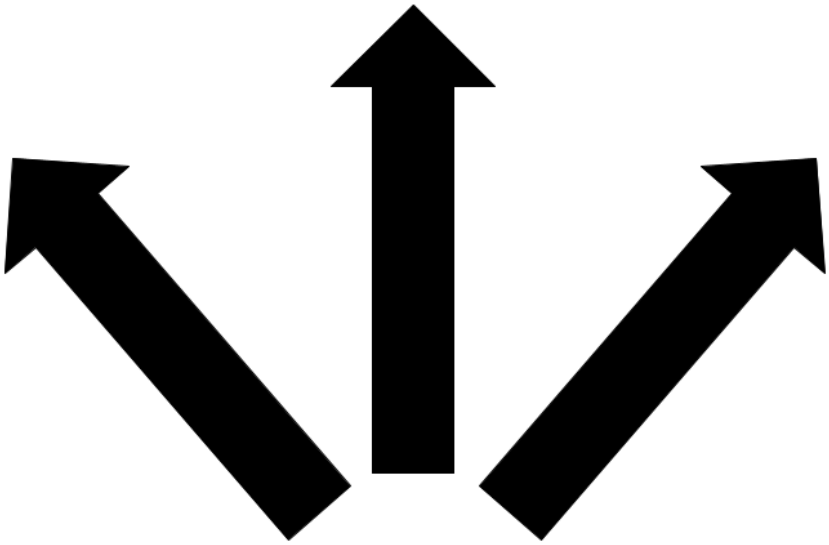
26. Do the dots you added give off light? Use Model 5 to explain how you know.

Summary

The dots you added stand for mass that pulls on stars and gas with gravity but gives off no light that we can detect. Astronomers call it **dark matter**. Rotation curves like M33's are some of the strongest evidence for dark matter.

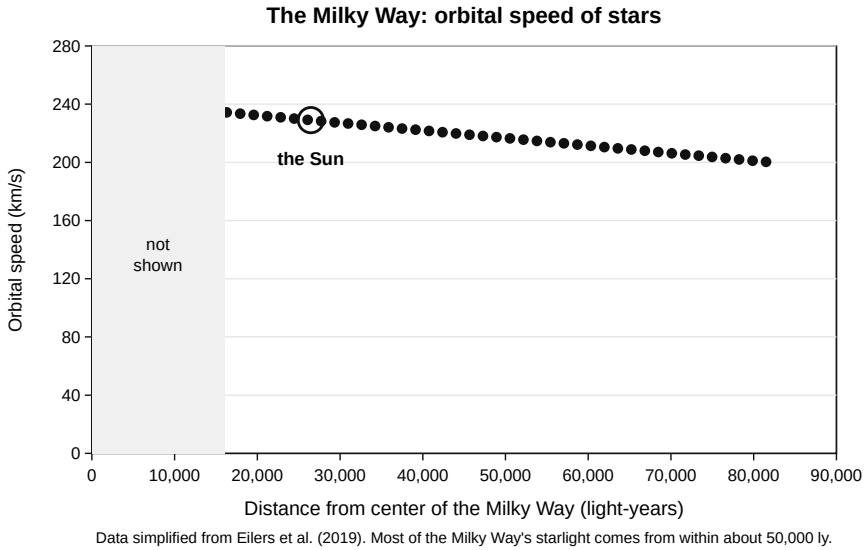
27. Complete the sentences. Dark matter is spread in a huge, roughly round cloud called a halo that reaches far beyond _____. We cannot see it, but we can detect it by its _____, which makes stars and gas orbit _____.

28. How many dots did you add, compared with the 29 dots of stars and gas? What does this suggest about how much of a galaxy is dark matter?



Apply

Model 6: Our galaxy. Astronomers have measured how fast stars orbit the center of the Milky Way at many distances. Most of the Milky Way's starlight comes from within about 50,000 light-years of its center.



Model 6. The Milky Way's rotation curve. The Sun is circled.

29. Is the Milky Way's rotation curve more like the planetary system (Graph 1) or like M33? Explain.

30. The speeds stay near 200 km/s even beyond 50,000 light-years, where there is little starlight. What does this tell you about the Milky Way?

31. The Sun orbits at about 230 km/s. If the Milky Way had no dark matter, would the Sun orbit faster or slower? Use the rule to explain.

Image and data credits

- M33 photo: NASA, ESA, and M. Durbin, J. Dalcanton, and B. F. Williams (University of Washington). Source
- M33 rotation curve and starlight: simplified from E. Corbelli et al., "Dynamical signatures of a ΛCDM-halo and the distribution of the baryons in M33," Astronomy & Astrophysics 572, A23 (2014). Source
- Milky Way rotation curve: simplified from A.-C. Eilers et al., "The Circular Velocity Curve of the Milky Way from 5 to 25 kpc," The Astrophysical Journal 871, 120 (2019). Source
- Planet speeds: NASA planetary fact sheets, rounded.
- All diagrams are original to this workbook.

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6: COSMOLOY

6.1: Look Back Time
6.2: Hubble Plots
6.3: Cosmology Models
6.4: Curvature and the Fate of the Universe

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6.1: Look Back Time

6.1 Look Back Time

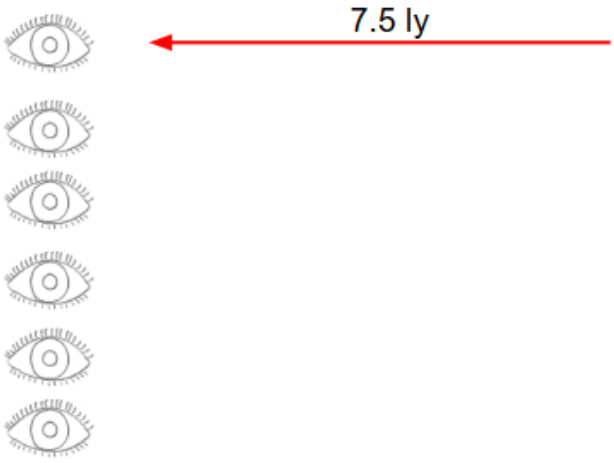
6.1.1 Light Year

Model

The table below shows 6 stars with different distances from an observer. The distances are measured in light years, which is the length of distance that light travels in a year. Imagine you are viewing all 6 stars at the same time.

1. The red arrow below represents how long the light traveled to get to your eye from **Star A**. Draw a similar arrow (scaled for size) for each of the other stars.
2. Which star is closest to the observer? How far away is it?
3. What was the greatest amount of time that it took the light from any one of the stars to you?
4. If each star appears to be 10 years old, how old is it actually (take into account the time it took for light to get to your)?

Star	Distance
A	7.5 ly
B	6.0 ly
C	9.2 ly
D	2.5 ly
E	8.7 ly
F	15 ly



Complete the blanks in the sentences of the following paragraph by filling in the correct response in the parentheses ().

- *The light from the star that is farthest from Earth will take the (greatest/least) amount of time to get to us. The star will be getting older this entire time, and therefore will be the (oldest/youngest) of all the stars if the appear to all be the same age right now.*

6.1.2 Look Back Time

Model

Imagine that you are observing the light from a ·distant star that was located in a galaxy 100 million ly away from you. By analysis of the starlight received, you are able to tell that **the image we see is of a 10-million-year-old star**. You are also able to predict that the star will have a total lifetime of 50 million years, at which point it will end in a catastrophic supernova.

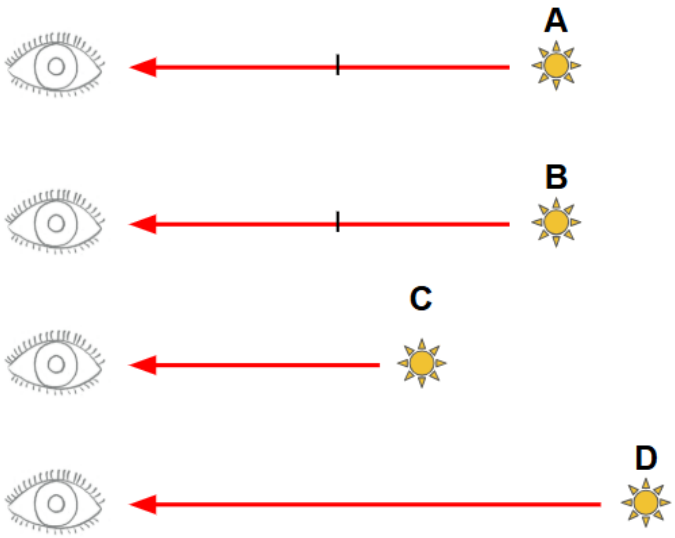


1. How old does the star appear to be to us here on Earth (Hint: read the text above the image)?
2. When we look at this star, how far back in time do we look? We call this the **Look Back Time**
3. How long will it be before we receive the light from the supernova event?
4. Has the supernova already occurred? If so, when did it occur? *Identify where along the diagram the supernova light is currently.*

6.1.3 Comparing Distances and Ages

Model

Imagine that you take images of four main sequence stars that have the same mass. From your observations, all stars **appear** to be the same age.



Determine the following:

- Are there any stars that ***actually are*** the same age? If so, which ones? Explain your reasoning.
- Which is the youngest star? How do you know?
- Which is the oldest star? How do you know?
- Which star tells you more about the past history of the universe? Explain your thinking.

Summarize: How can astronomers use the idea that light has a specific speed to explore the past?

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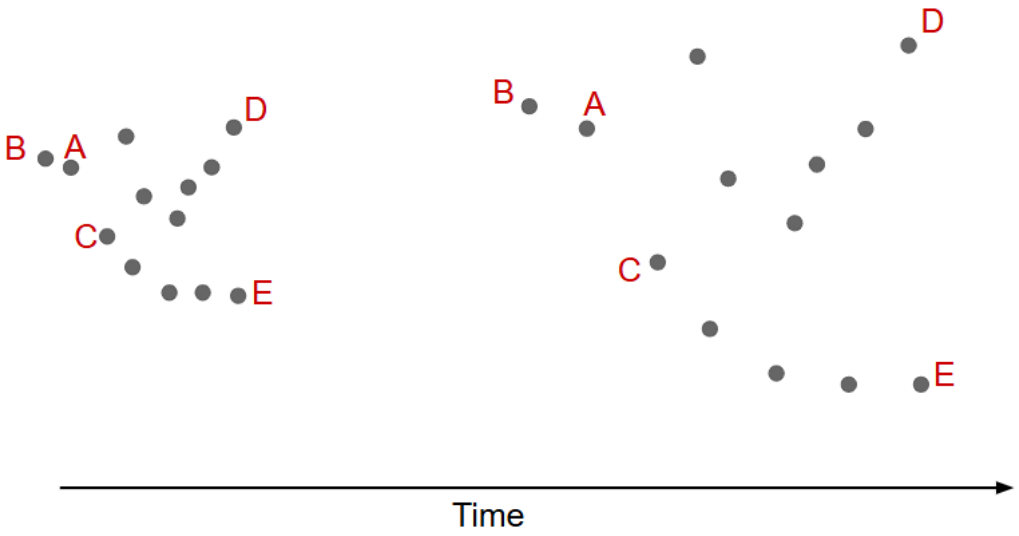
6.2: Hubble Plots

6.2 Hubble Plots

6.2.1 Expansion of Space

Model

The dots below represent different **galaxies** in the universe. Two snapshots are shown, the time increasing to the right.



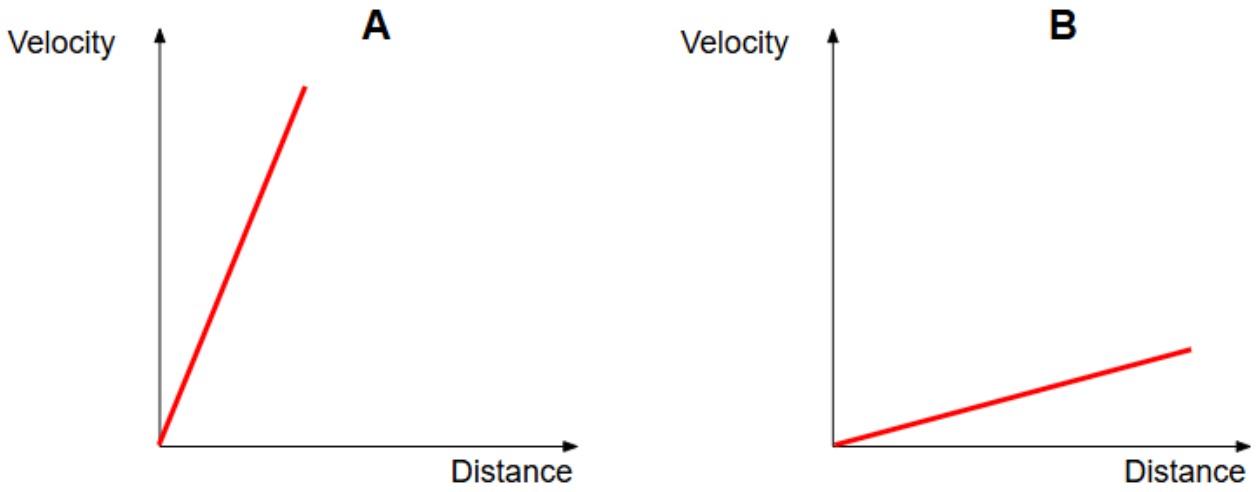
1. Examine the distance between the galaxies labeled A-E in the Early Universe. Are all the galaxies the same distance from each other?
2. Describe how the universe changed in going from the Early Universe to the Universe Some Time Later.
3. Do the galaxies appear to get bigger?
4. Based on your answer to Question 3, do you think the stars within a galaxy move away from one another due to the expansion of the universe? Explain your reasoning.
5. Compare the amount that the distance between the A and B galaxies changed in comparison to the amount that the distance between the A and D galaxies changed.
   Which galaxy, moved the farthest from A?
6. If you were in the A galaxy, how would the B, C, D, and E galaxies appear to move relative to your location?
7. If you were in the A galaxy, how would the B, C, D, and E galaxies all appear to move the same distance in the time interval from the Early Universe to the Universe Some Time Later?
8. Imagine that you are still in Galaxy A. Rank the B, C, D, and E galaxies in terms of their relative speeds away from you, from fastest to slowest.
9. Now imagine that you are in the E galaxy. Rank the A, B, C, and D galaxies in terms of their relative speeds away from you, from fastest to slowest.

10. Is there a relationship between an object's distance away from you in the universe and the speed it would appear to be moving away from you? If so, describe this relationship.

6.2.2 Comparing Hubble Plots

Model

Below are two plots that show the relative speed of a galaxy to an observer and the distance between the observer and the galaxy.

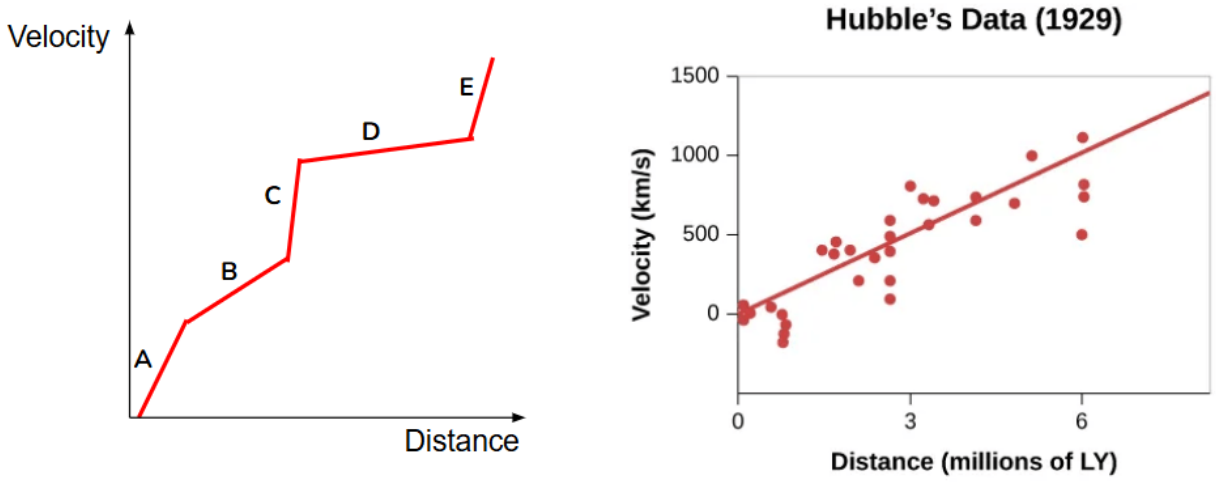


1. Which plot (A or B) represents an universe that is expanding **faster**?
2. What property of the plot determines the **rate of expansion**?

6.2.3 Analyzing Hubble Plots

Model

Consider a Hubble Plot below that shows the relative speed of a galaxy to an observer and the distance between the observer and the galaxy. This plot does not represent real data or our universe



Right Image Credit: OpenStax Astronomy 2e (https://openstax.org/details/books/astronomy-2e)

Examine the plot on the Left:

1. Which section shows a galaxy that is moving away quickly but a universe that is expanding slowly?
2. Which section shows a galaxy that is moving away slowly but a universe that is expanding quickly?
3. Which section represents a galaxy moving away at a medium speed in a universe that is expanding very quickly?

Recall that when we look at objects that are ***farther away*** we see them as they were ***further into the past***. **Examine Hubble's actual data (right)**

5. Which galaxies (dots on the graph) represent and earlier time in the universe (further in the past)?
6. Which galaxies represent the more recent universe?
7. Is the expansion rate of the universe the same for each of these parts of the graph?

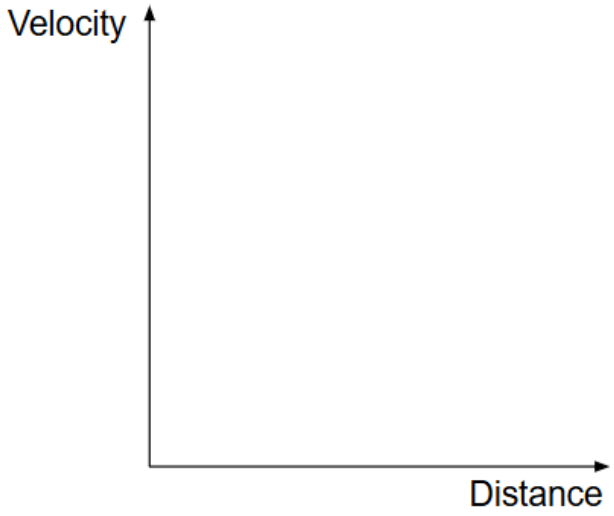
6.2.4 Building Hubble Plots

Model

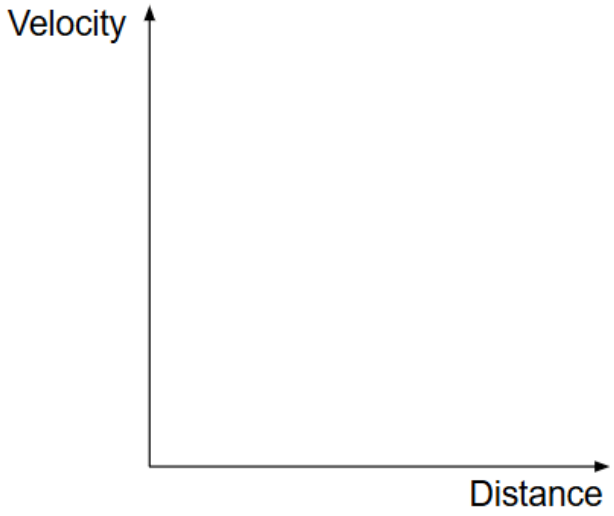
Create Hubble plots for possible universes:

- Draw one graph to represent a Hubble Plot for a universe that is expanding quickly now, expanded less quickly in the recent past, and very quickly in the distant past.
- Draw another graph to represent a Hubble Plot for a universe where the rate of expansion is quick now but was slow in the past.
- Draw one graph to represent a Hubble Plot for a universe that is **not expanding at all and never has**
- Draw another graph to represent a Hubble Plot for a universe where the rate of expansion has **continuously increased with time**.









6.2.5 Hubble Plot (updated) for our Universe

Model

More data has been collected since Hubble. The plot below shows an approximate plot of the galaxies in our universe.

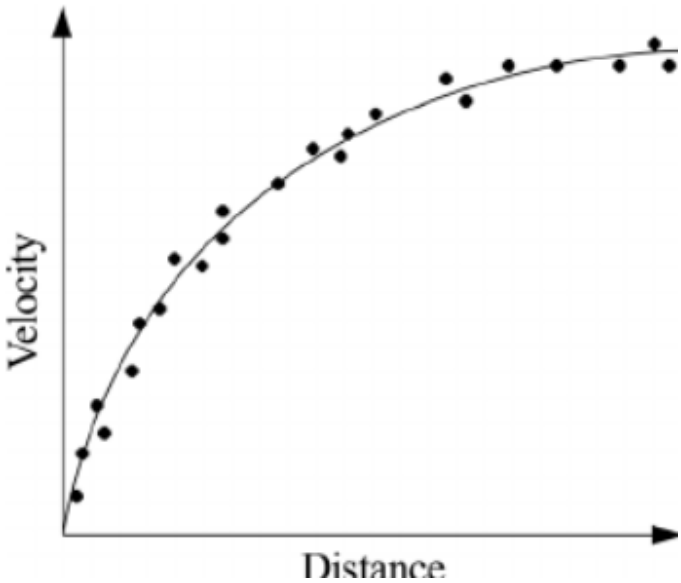


Image Credit: Wallace, Colin & Prather, Edward. (2012). Teaching physics with Hubble's law and dark matter. American Journal of Physics. 80. 382-390. 10.1119/1.3684469.

Mark up the diagram:

- Draw a circle around the galaxies from which we receive light that was emitted closest to our present time.
- Draw a square around the galaxies from which we receive light that was emitted furthest from our present time.
- Write the letter C, and next to the galaxies that are moving away from us with the fastest velocities.
- Write the letter D next to the galaxies that are moving away from us with the slowest velocities.
- Write the letter E next to where it has the steepest slope.
- Write the letter F next to where it has the flattest slope.
- Write the letter G next to the portion of the graph that corresponds to the fastest expansion rate.
- Write the letter H next to the portion of the graph that corresponds to the slowest expansion rate.

Analyze the results

1. Would you say that the expansion rate of the universe is constant or changing with time? Explain your reasoning.

2. Is the expansion rate represented by the motion of galaxies far away from us faster than, slower than, or the same as the expansion rate represented by the motions of nearby galaxies? Explain your reasoning.

3. Is the expansion rate of the universe increasing or decreasing as time goes on? Explain your reasoning.

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6.3: Cosmology Models

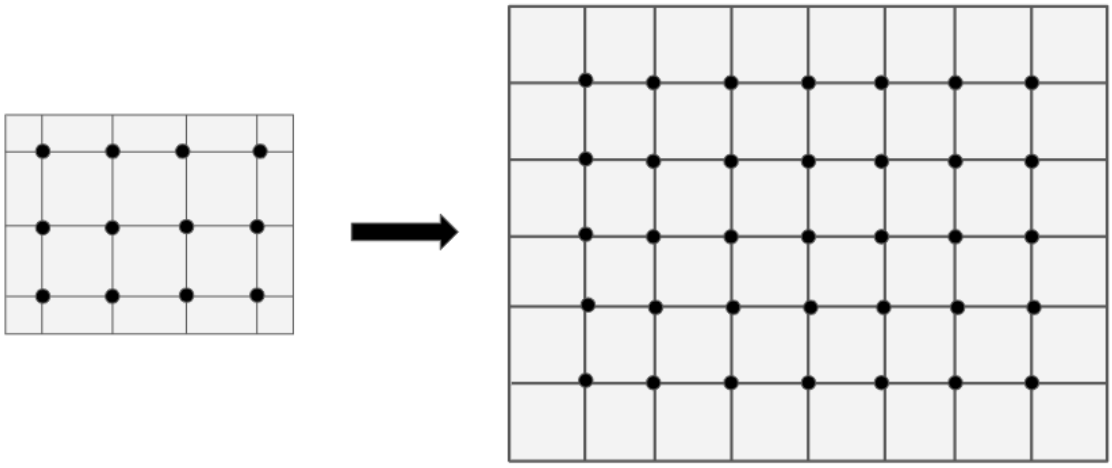
6.3 Expansion Models

6.3.1 Cosmology Models

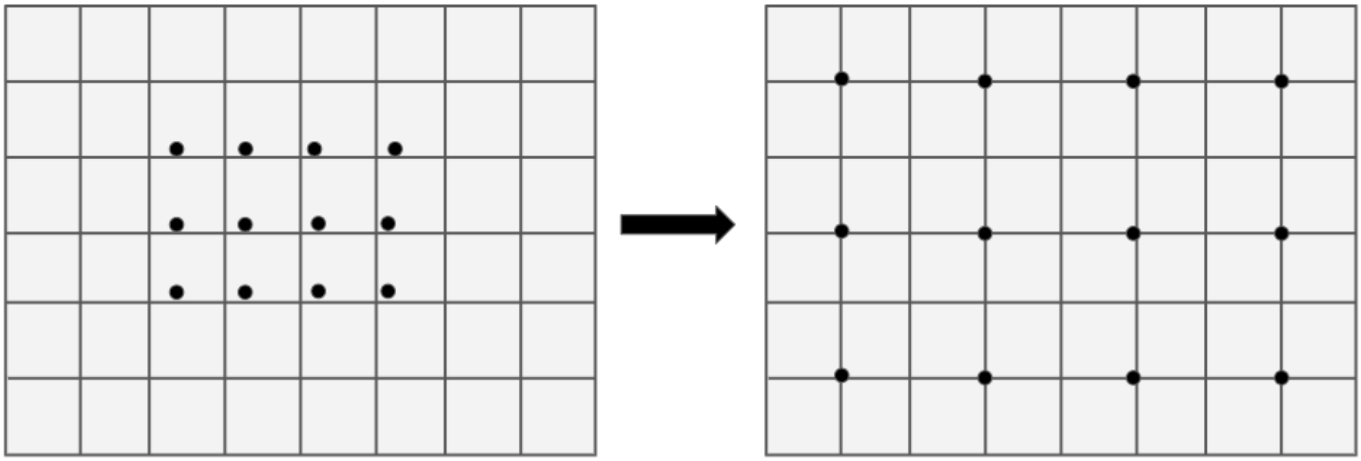
For each mode below, identify the following:

- The **size of the universe** (total box size) increases / decreases / remains the same
- The **amount of matter** (dots) increases / decreases / remains the same
- The **grid spacing** increases / decreases / remains the same

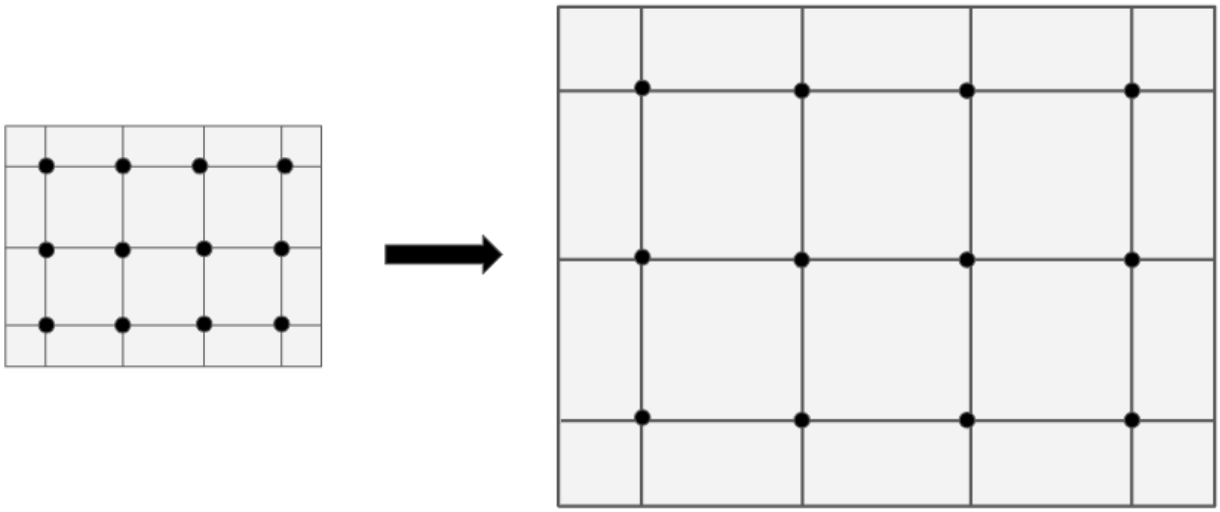
Model A: Steady State



Model B: Mass Filling



Model C: Universe Growing



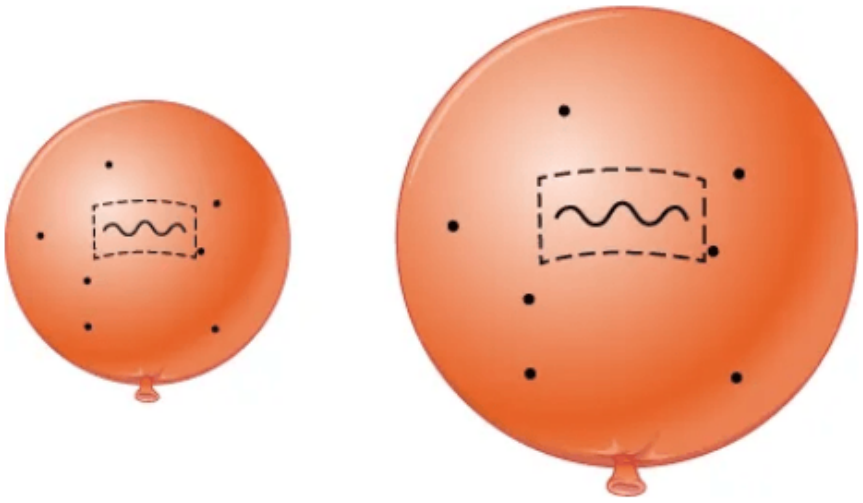
Summary Question

Which model do you think represents how our universe is growing? Explain your reasoning.

6.3.2 Balloon Analogy

Model

One way to model the expanding universe is to use a "balloon" analogy. In this analogy, the space and time of the universe are modeled by the "surface" or "skin" of an expanding balloon. ***The entire universe exists only on the surface of the balloon***. Light can travel only in the space and time along the surface of the balloon.

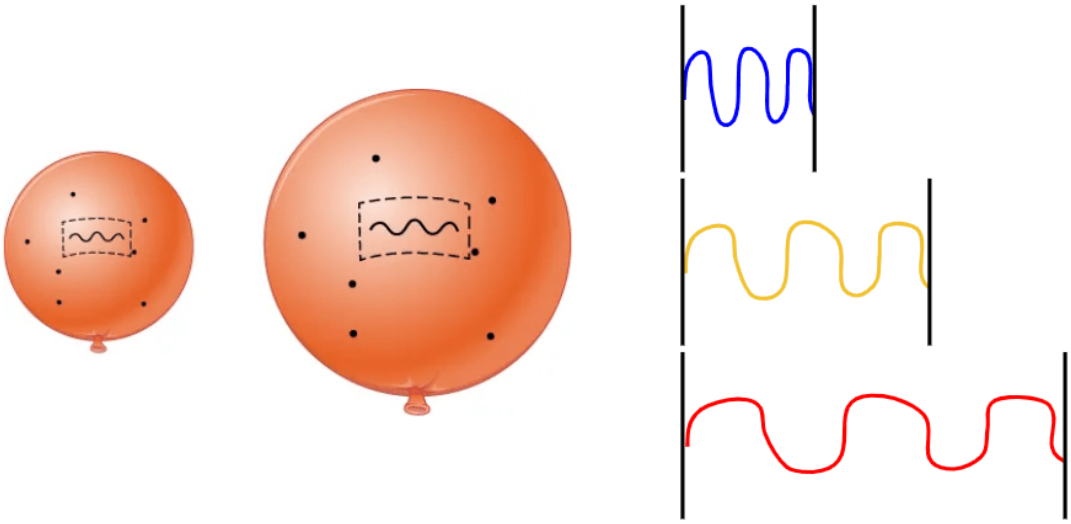


1. Do objects, light, or events in the entire universe also exist inside or outside of the balloon's surface in this analogy?
2. If you were to travel from galaxy to galaxy along the surface of the balloon, would you ever encounter an edge?
3. If you were to travel over the entire surface of the balloon universe, would you ever find a location that is the center of the entire universe?
4. Imagine you lived in a galaxy on the surface of the balloon. As the balloon expands, would all the other galaxies appear to move toward you or away from you?
5. Would your answers to the previous question be the same regardless of the galaxy in which you live, or would it change depending on the galaxy you inhabit?
6. In this analogy, do galaxies move relative to one another because they are traveling across the surface of the balloon, or do they move relative to one another because the balloon is expanding?

6.3.3 Cosmological Redshift

Model

The same balloon model shows a wavelength of light that is traveling across space while space (the balloon) expands. Next to it is a reminder of how expanding light results in a redshift (even if it doesn't actually include a red wavelength).



As a wave of light travels, space expands.

1. What happens to the wavelength of the light as it travels?
2. What happens to the color of light as it travels?
3. Suppose you see a distant star that appears to be yellow. Because of the expansion of space, the original light was: Blue/Yellow/Red
4. Which color represents a hotter star, yellow or your answer to question 3?
5. When we look at distant stars, will the color of the light we receive cause us to think the stars are hotter or colder than they really are? Explain.

Summary

Cosmological Redshift is usually identified as the ratio of observed wavelength to emitted wavelength:

$$Z = \frac{\Delta\lambda}{\lambda_e} \tag{6.3.1}$$

$$\Delta\lambda = \lambda_o - \lambda_e \tag{6.3.2}$$

- λ_e is the wavelength of light that is **emitted** from the source
- λ_o is the wavelength of light that is measured by the **observer**

The amount that the light is redshifted is based on the expansion of the universe:

$$\frac{R_o}{R_e} = (1 + Z) \tag{6.3.3}$$

- R_e is the radius of the universe when the light is emitted
- R_o is the radius of the universe when the light is measured by the observer

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6.4: Curvature and the Fate of the Universe

6.4 Curvature and Fate of the Universe

Analogy and Background

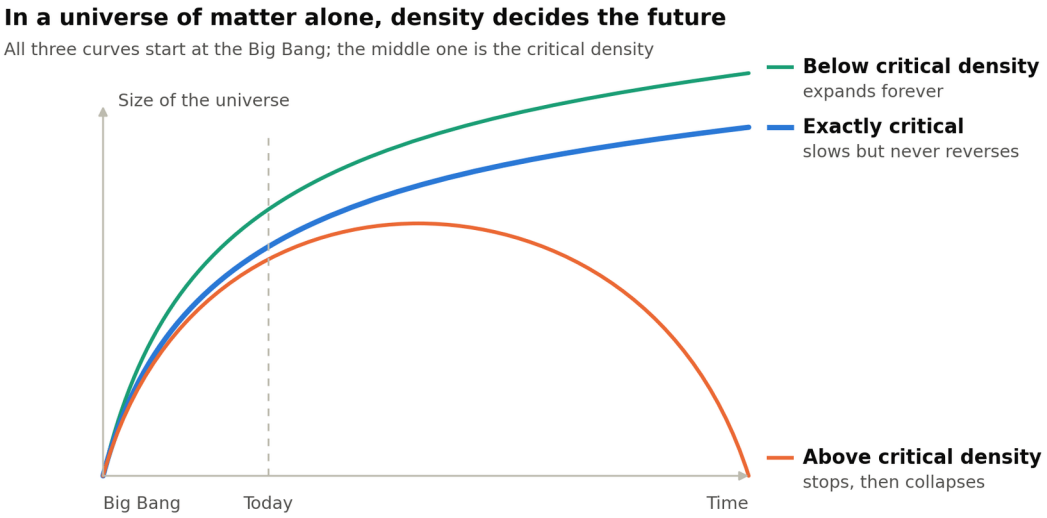
Throw a ball upward and gravity pulls it back. Throw it slowly and it falls back down. Throw it hard enough and it escapes forever. At one special speed, the escape speed, it slows more and more and only stops after an infinite time.

A universe made of matter alone behaves the same way, because the gravity of all that matter pulls back on the expansion. The density that separates the two outcomes is called the critical density. It is tiny: only a few hydrogen atoms in every cubic meter of space. If the real density is above the critical density, gravity wins and the expansion eventually reverses. If it is below, the expansion goes on forever.

6.4.1

Model

The curves show the size of the universe over time. All three start at the Big Bang, and the middle curve is the critical density.



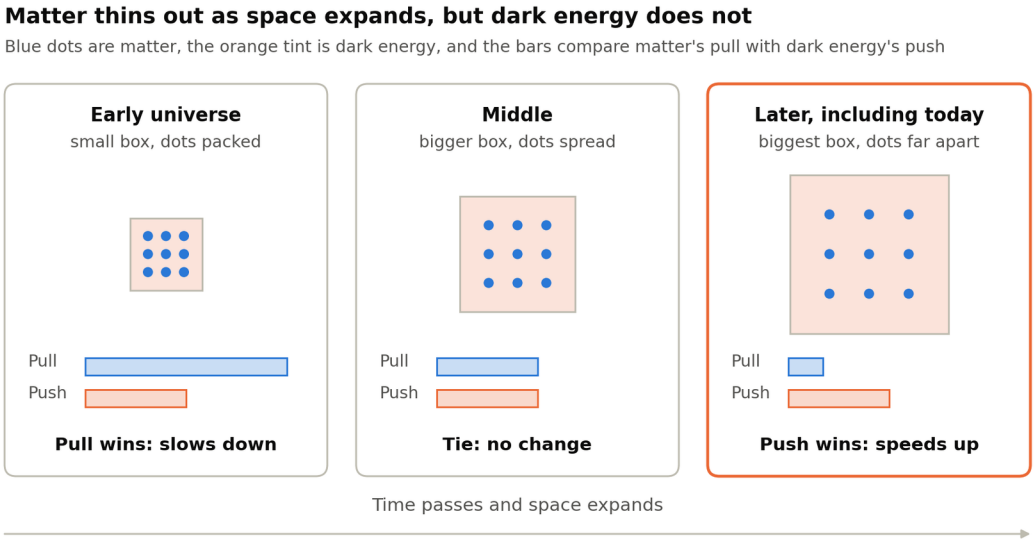
1. Match each curves expansion rate to a ball thrown:
    1. **too slowly**
    2. At **exactly at escape speed**
    3. thrown **faster than escape speed**.
2. Explain your matches from question 1
3. In your own words, what does "critical density" mean?
4. In a universe made only of matter, could the expansion **ever speed up**? Explain why or why not.
5. Astronomers find that the expansion today **is speeding up**. Does that make sense based on gravity alone or does there need to be something else?

6.4.2 Mass Density and Dark Energy

Model

As space expands, matter spreads out. The same dots fill a bigger box, so matter's density drops and its gravitational pull on the expansion fades. Dark energy behaves differently. As far as we can tell, dark energy has the same density no matter how much space there is. Every new piece of space brings its own dark energy, so its outward push does not fade. Early on, matter's pull was far stronger. As the universe grew, the pull weakened until the push took over. That switch happened roughly 5 to 6 billion years ago, and the expansion has been speeding up since.

In the diagram, the bars compare matter's pull with dark energy's push at three moments in cosmic history.



1. What happens to the matter dots as the box grows? Why does that weaken gravity's pull? (Hint: Recall how mass and distance affect the force of gravity)
2. There is another force shown in all three boxes. Does it grow, shrink or remain constant?
3. In the middle box the pull and the push are equal. Will this cause expansion to:
    - Accelerate
    - Decelerate
    - Neither
4. Label each panel with the rate expansion is changing. Explain your reasoning:
    - Accelerating Expansion
    - Decelerating Expansion
    - Expansion at a Constant Rate

6.4.3 Curvature of the Universe

Model

6.4.4 Fates of the Universe

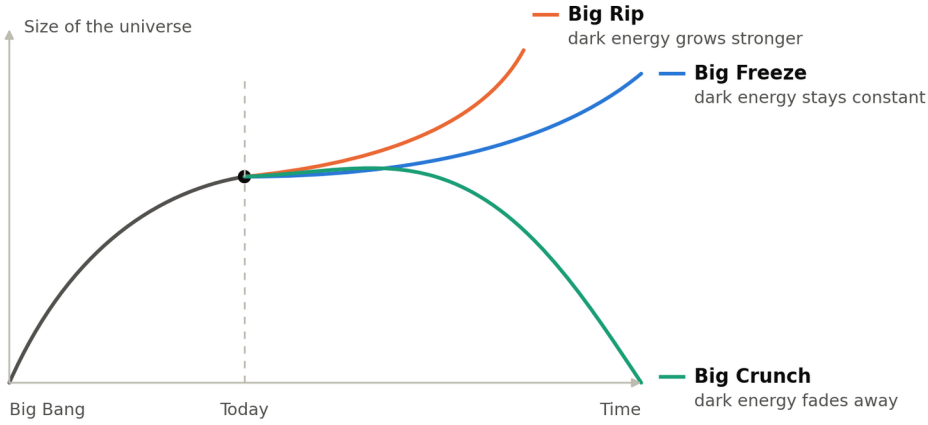
Model

The far future depends on how dark energy behaves over billions of years. The curves share the same past. They split only in the future, depending on what dark energy does.

- **Big Freeze.** If dark energy stays constant, the expansion keeps speeding up forever. Distant galaxies slip beyond our view, stars burn out, and the universe grows cold and nearly empty.
- **Big Crunch.** If dark energy fades away, matter's gravity wins again. The expansion slows, stops and reverses, and everything falls together into a hot, dense collapse.
- **Big Rip.** If dark energy grows stronger, its push eventually overwhelms every force that holds things together. It tears apart galaxies, then stars and planets, and finally atoms.

The future depends on how dark energy behaves

Same history up to today, three possible futures



1. Fill in the table to match each dark energy scenario to a fate.
2. Which fate do the current measurements favor, and how confident are scientists? What new result would make you change your answer?
3. In a Big Rip, why would galaxies be torn apart before atoms? Think about which structures are held together most weakly.
4. Suggest one kind of measurement that could help tell the three fates apart.

Scenario	Fate	What happens to galaxi
A. Dark energy stays the same strength forever		
B. Dark energy fades away		
C. Dark energy grows stronger over time		

Where do the measurements stand? A constant dark energy still fits most of the data, which points to a Big Freeze. Some recent analyses that combine galaxy surveys, supernovae and the cosmic microwave background hint that dark energy may be weakening over time, but the evidence is not yet strong enough to count as a discovery. Results from the full five-year DESI galaxy survey are expected in 2027. If dark energy keeps weakening, a Big Crunch becomes possible, so this is an active research question.

Summary

Finish each sentence in your own words, then compare with another team.

In a universe with only matter, the critical density is the dividing line between _____ and _____.

As space expands, matter's density _____ but dark energy's density _____, so _____ eventually wins the tug of war.

Three clues for dark energy are _____, _____ and _____.

The fate of the universe depends on whether dark energy _____.

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