Star and Planet Formation

These classroom materials were prepared for high-school-level physics and astronomy.

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National Aeronautics and
Space Administration

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Star Classifications

According to the Hertzsprung-Russell Diagram

When stars are plotted on the Hertzsprung-Russell (H-R) diagram (see below) according to their brightness (luminosity) and color (temperature), a pattern begins to emerge. This pattern helps astronomers classify the stars. (See **Star Patterns** on next panel.)

The H-R diagram is named after two scientists, Einar Hertzsprung and Henry Russell, who independently discovered a relationship between a star's temperature and its true brightness. This relationship is the unifying concept that opened the door to a new era of understanding and discovery. This concept is as important to astronomers as the periodic table of elements is to chemists. And although all stars form in the same way, condensing from clouds of dust and gas, they can vary in size, composition, temperature, brightness, and color. And many of these properties are related to each other.

Create your own H-R diagram by using the data in the Table of Star Temperatures and Absolute Magnitudes shown below. Plot the temperature against the brightness of each star on the blank H-R diagram.

The surface temperature of each star is given in kelvins (K), and the brightness of the star is adjusted as if each star were observed from the same distance; this indicates the star's absolute magnitude. (Notice that the brighter the star, the lower its magnitude.) Conversions: 1 kelvin unit = 1° C; 32° F = 0° C = 273 K.

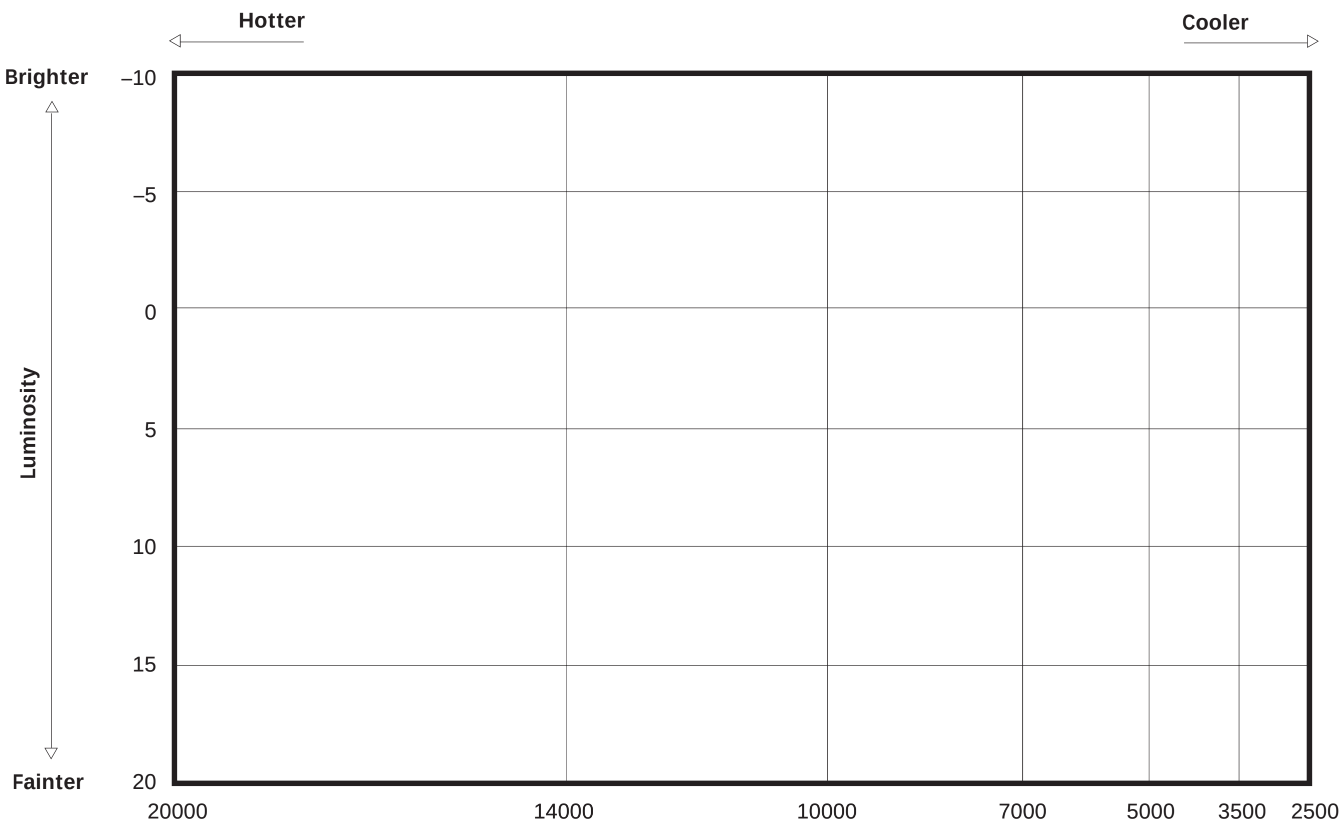


Table of Star Temperatures and Absolute Magnitudes

Temp	Abs Mag	Temp	Abs Mag	Temp	Abs Mag	Temp	Abs Mag	Temp	Abs Mag
23000	–2	7500	1.5	5600	4	4700	6.5	3700	0.5
19000	2.5	7300	14	5500	4	4600	2	3700	9
15000	11	7250	1	5500	6.5	4500	0.5	3600	0
13000	–7.5	7000	12	5200	5	4400	2	3600	10
13000	–1	7000	3.5	5100	2.5	4400	8	3500	–1
11000	1.75	6750	2	5100	6	4300	–1	3500	11
9800	13.5	6500	15	5000	–4.5	4300	7.5	3400	–0.5
9400	0	6500	3	5000	1	4200	1	3400	12.5
9000	12.5	6300	4.5	5000	0	4150	9	3200	1
9000	2	6200	3.5	5000	7.5	4000	–1.5	2100	–2
8700	4	6100	14	4950	8	4000	8	3000	13
8500	–2	6100	5	4900	–1	3900	1	2700	–6
8000	1	5800	7	4900	6.5	3800	–0.5	2700	14
7800	12.5	5700	16	4850	2	3800	8	OUR	SUN
7700	3	5700	5.5	4700	0.5	3700	–5.5	5800	4.8

Classifying Stars

A star's temperature can be determined by the precise color of the light given off at its surface. This is true because we know any given substance will glow with a specific color when it is heated to a specific range of temperatures. Stars are divided into seven classes based on their surface temperatures. Each class is known by its letter name and each classification represents a certain color and temperature range.

The temperature and therefore color of a star is determined by the types of nuclear reactions that occur in its core. These reactions depend on the mass of the star. In the Table of Star Temperatures and Absolute Magnitudes, a star's mass is always given in relation to the mass of the Sun. This means a mass of 2 equals twice the mass of our Sun. Please note that the most massive stars also have the highest temperatures and the shortest life spans. At the higher temperatures, nuclear fusion takes place more efficiently and the star runs out of fuel much faster than does a smaller star.

Across the top of your H-R diagram, write in the star classification for each temperature range.

A star's observed brightness depends on both its diameter and its distance from the observer. This explains why larger stars tend to be more luminous. Of the two variables, a star's distance has the greater effect on its apparent brightness. Therefore, to get an accurate comparison, you must take into account the stars' distances from Earth. This is done by measuring each star's brightness as if it was measured from the same distance. This measurement, then, is the star's absolute magnitude. Examine your completed H-R diagram. Do you see areas where the stars seem to be concentrated, and other areas where there appear to be no stars?

Label the following groups of stars on your H-R diagram.

Star Classification Chart

Class	Color	Temperature (K)	Example	Life Span (Years)	Mass (x Sun)
O	deep blue	30,000+		1 million	40
B	bluish	11,000–30,000	Rigel	80 million	7
A	blue-white	7500–11,000	Sirius	2 billion	2
F	white	6000–7500	Procyon, Polaris	10 billion	1.3
G	yellow	5000–6000	Sun, Capella	20 billion	1
K	orange	3500–5000	Aldebaran	50 billion	0.8
M	red	<3500	Proxima Centauri		

Star Patterns

Main Sequence – The majority of stars appear in a roughly diagonal line stretching from the upper left corner of the diagram to the lower right. These stars are known as main-sequence stars. They are the most numerous, and live fairly stable, long lives.

White Dwarfs – A narrow cluster of stars can be found below the main sequence and a little to the left. These stars were previously on the main sequence but have now exhausted most of their fuel and collapsed into tiny spheres. They are quite hot, but are not very bright because their diameters are so small. This forms the last stage of a typical star's life.

Red Giants – These stars are found slightly above and to the right of the main sequence. Scientists believe a red giant star forms from a main sequence star that has run out of fuel. An outer shell of gas is pushed up and away, which then expands and cools. This dramatically increases the diameter of the star and lowers its surface temperature. These giant stars tend to be red or orange in color because they are cooler.

Super Giants – Some rare stars are exceptionally large. Because of their incredibly large diameters, they look extremely bright even though they may have lower, cooler temperatures.

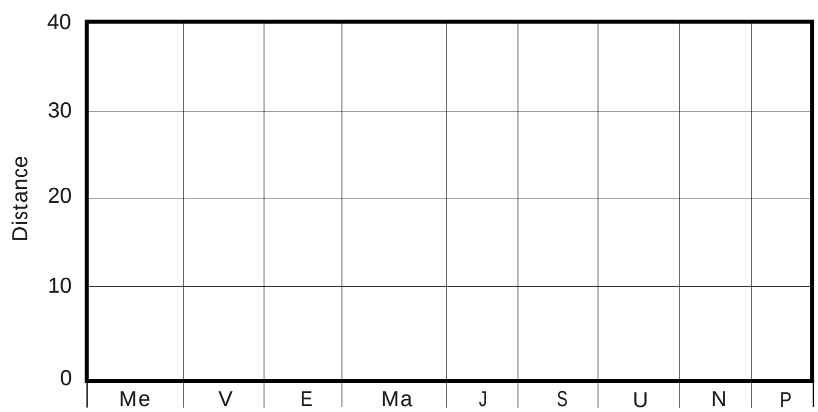
Planetary Worksheet — 1

The mounting evidence (including the recent images from the Hubble Space Telescope) that there are planets outside of our own solar system raises important questions as to whether or not we are the only life form in the universe. Hubble pictures show what appears to be a disk-shaped cloud of condensing gas. These remains of a supernova explosion could be the earliest stages of the formation of a solar system just like our own. Studies by other telescopes probing certain nearby stars reveal a telltale wobble in their positions. This could indicate the presence of Jupiter-size planets in orbit around them. If the Keck and Space Interferometry Mission (SIM) interferometers verify the existence of these planets, the search for life could center on those most similar to Earth. The following exercise will help you to discover the range of differences and similarities among the nine planets circling our own Sun.

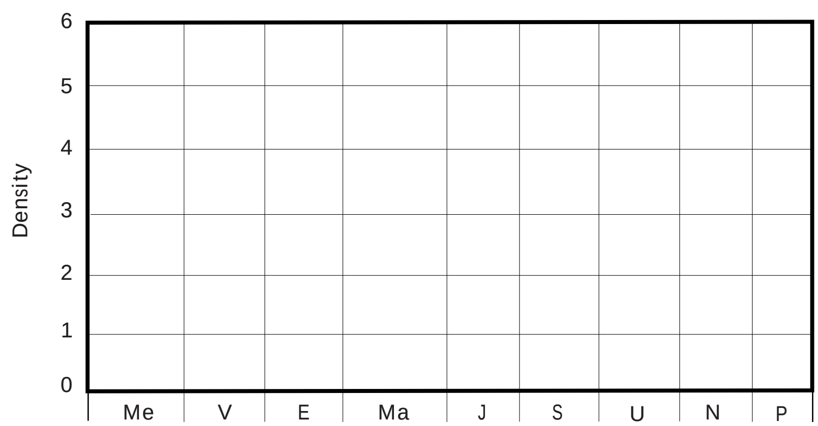
Plot the following NASA planetary data into the four graphs provided. Notice the patterns in the planet groupings in your completed graphs and use them to answer the questions on the following worksheet. ”Distance“ in the table below refers to the average distance from the Sun to the planet as given in astronomical units (AUs) — 1 AU is the distance between the Sun and Earth. One orbital period is the time it takes a planet to go around the Sun once, as compared to one Earth year.

Planet	**Distance (AU)**	**Orbital Period**	**Planet Mass**	**Density (g/cm^3)**	**Rotation (hr)**
Mercury	0.387	0.24	0.06	5.44	1408
Venus	0.723	0.62	0.082	5.25	5832
Earth	1	1	1	5.52	23.93
Mars	1.524	1.88	0.11	3.94	24.62
Jupiter	5.202	11.86	317.89	1.33	9.92
Saturn	9.555	29.46	95.18	0.69	10.66
Uranus	19.218	84.01	14.54	1.27	17.24
Neptune	30.019	164.79	17.15	1.64	16.11
Pluto	39.439	247.68	0.002	2	153.3

Planet vs. Distance from Sun

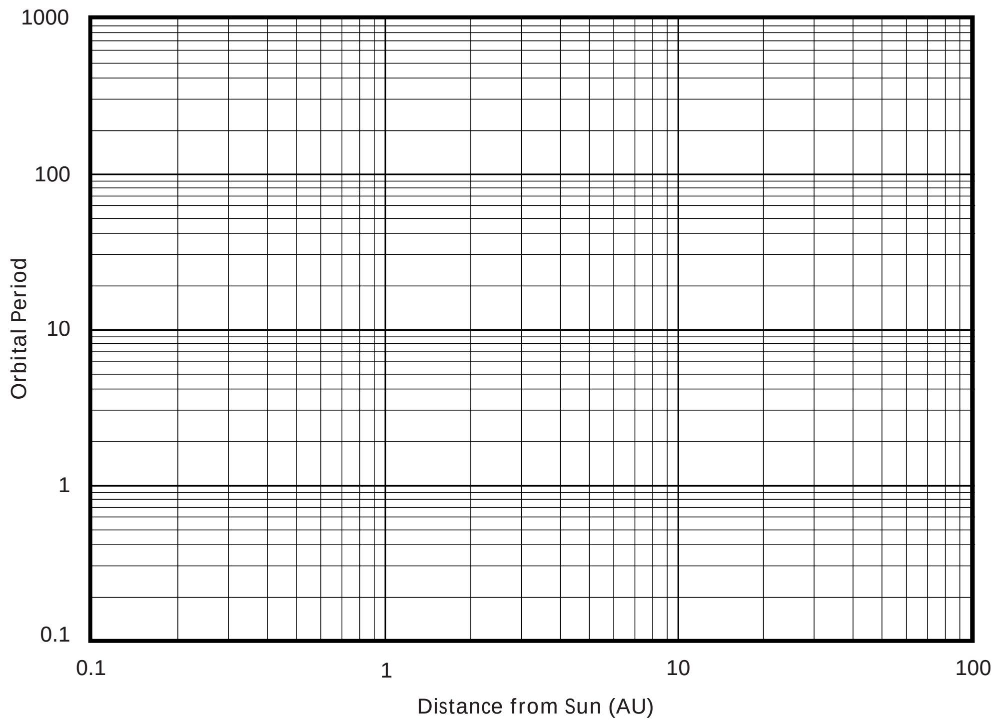


Planet vs. Density (g/cm^3)

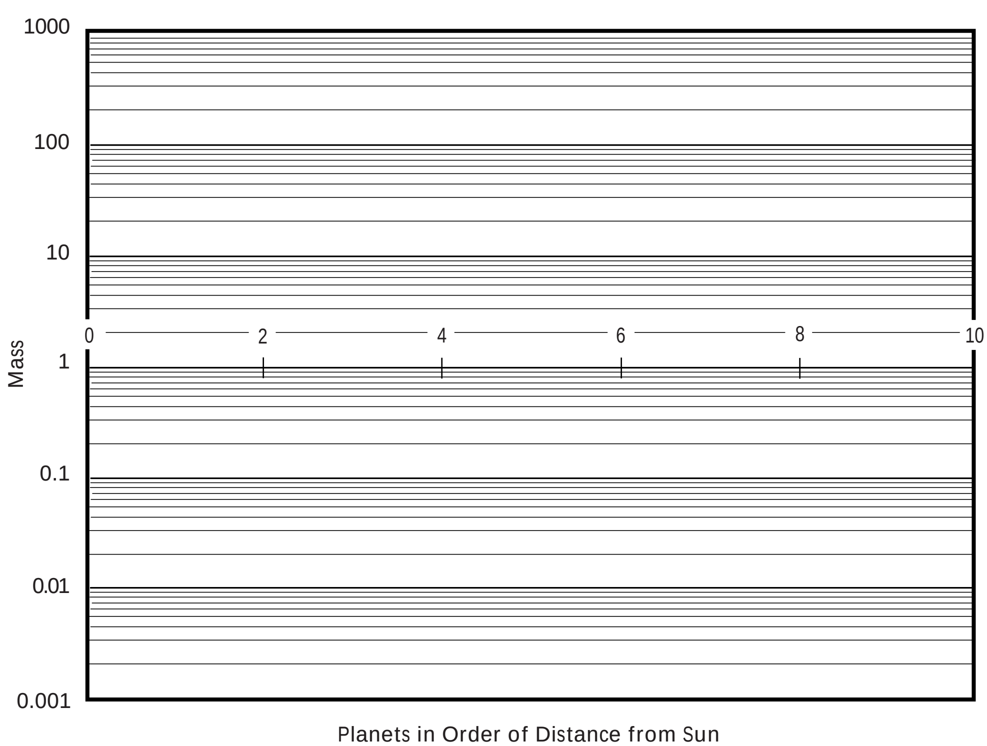


Planetary Worksheet — 2

Orbital Period vs. Distance from Sun



Planet Mass



Planets of Our Solar System

Our solar system consists of a single G-class star (see the **Planetary Worksheet** for more information) orbited by nine planets of varying sizes and compositions. Their names are derived from ancient mythology, each planet representing a different deity. Since all of the planets orbit in the same plane and in the same direction, they probably formed from the same protoplanetary disk of cooling dust and gases. Yet, each of these planets has a unique personality and is quite different from the others.

Rocky Earth-Like Planets

Mercury – As the closest planet to the Sun, Mercury is extremely hot (427° C facing the Sun). Its atmosphere was blown away long ago by intense solar radiation, leaving it vulnerable to asteroid and meteor impacts. Its most visible features are its numerous craters, similar to those on our own Moon.

Venus – Similar in size to Earth, Venus also has a thick atmosphere. Unlike Earth's atmosphere, however, that of Venus is composed of carbon dioxide gas and is topped by thick clouds of sulfuric acid. The cloud cover traps a lot of solar energy, keeping the ground temperature on Venus higher than that of any of the other planets (470° C).

Earth – Earth's distance from the Sun, coupled with its atmosphere, allows it to have just the right environment for liquid water to exist in great abundance; its ground temperatures are usually between 0° and 100° C. All life, as we know it, depends on liquid water for its existence. Water also plays a big role in changing Earth's surface. Shifting crustal plates build up mountains, and snow and rain erode them away, providing a constantly changing geography. Searches for life on other planets will likely begin with a search for liquid water.

Mars – This reddish planet gains its color from rusting iron in its soil. Like Earth, its day lasts about 24 hours, and its axis is tilted, giving it seasons and polar ice caps. Mars has the solar system's largest volcano. The presence of frozen water at its poles hints at the possibility of life there.

Gaseous Giant Planets

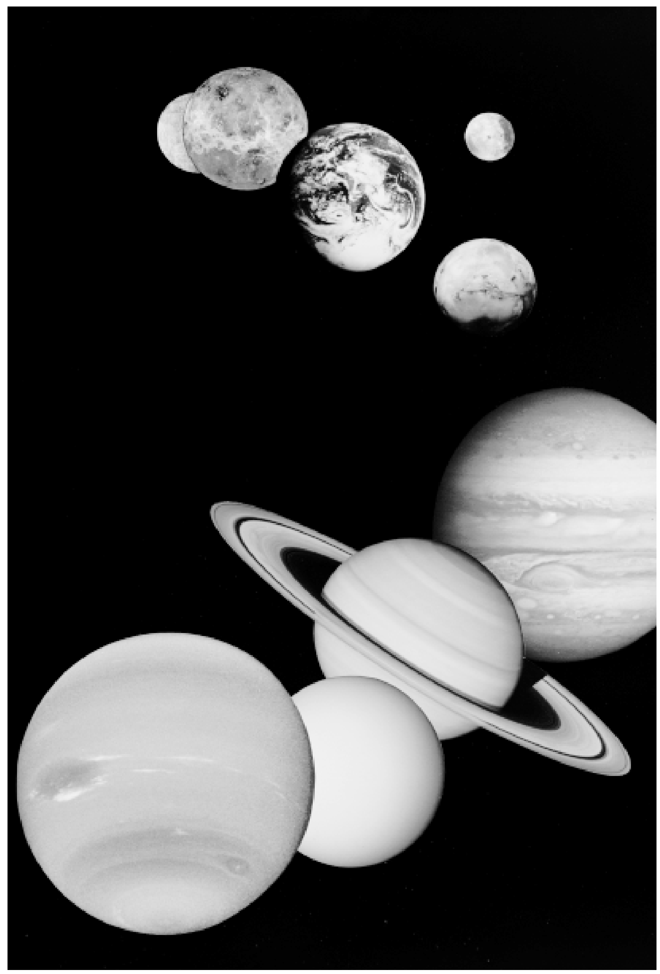
Jupiter – Unlike the first four rocky planets, Jupiter is made up mostly of hydrogen with some helium gas mixed in. Although it is the largest planet in our solar system, its mass is not quite large enough for it to turn into a star. Vast storms race through its thick atmosphere. Most famous of these persistent and long-lasting storms is the Great Red Spot. This storm covers an area that measures three times the diameter of planet Earth. Four of Jupiter's moons are large enough to see from Earth with binoculars. One of them, Io, is the most volcanically active body in the solar system.

Saturn – Magnificent rings of ice, rock, and dust surrounding this gaseous giant serve to identify Saturn easily. Saturn also possesses 18 moons, the most of any planet. Of particular interest is its largest moon, Titan. Scientists think Titan may have an atmosphere similar to that of prehistoric Earth. The least dense of all planets, Saturn would float if placed in water, being composed mostly of hydrogen gas.

Uranus – Another of the gaseous giants, Uranus, has a ring system about it, although on a much smaller scale than Saturn's. Uranus is strongly tilted on its side. And the presence of methane in its atmosphere gives it a greenish blue color.

Neptune – Astronomers discovered Neptune by observing the irregularities in Uranus' orbit. Neptune, the last of the gaseous giant planets, has large, violent storms (like the Great Dark Spot and Scooter), which were photographed in detail by the Voyager spacecraft.

Pluto – The smallest of the nine planets, Pluto is considered by some astronomers to be a double planet because its companion moon, Charon, is fully half the size of Pluto itself. Its distant orbit brings Pluto around the Sun only once in 248 years and makes it the coldest planet in our solar system. At its nearest approach to the Sun, it has a thin atmosphere; but in its outer orbit path, the atmosphere freezes and "collapses" to the planet's surface. In this regard, Pluto even acts like a comet. Where does Pluto fit? Should it be one of the gaseous planets since its orbit keeps it in line with them? Or should it be a terrestrial planet because of its rocky nature?



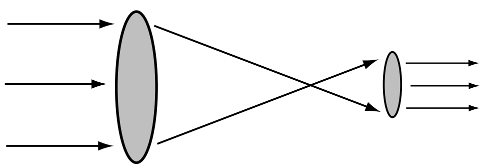
This image is a composite of all the planets in our solar system, except Pluto. At top left, we see Mercury, next is Venus, then Earth with its Moon to the right, followed by Mars, Jupiter, Saturn, Uranus and, at lower left, Neptune.

Tools of the Trade

The tools used to observe the heavens have changed dramatically since the first telescopes were invented. The purpose of an optical telescope is to gather whatever faint light is available from distant objects and focus it into an image. Telescopes' capabilities are measured according to two attributes:

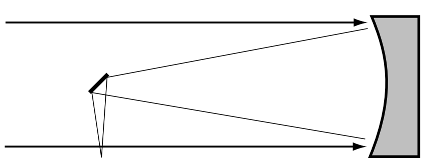
Light-Gathering Capability – This is determined by measuring the mirror's total surface area. The larger the diameter, the greater the light-gathering capability.

Resolving Power – The telescope's baseline determines the sharpness of the images it can deliver. The baseline is the measured distance from one edge of the telescope's mirror or lens to its opposite edge. The longer the baseline, the greater the telescope's resolving power.



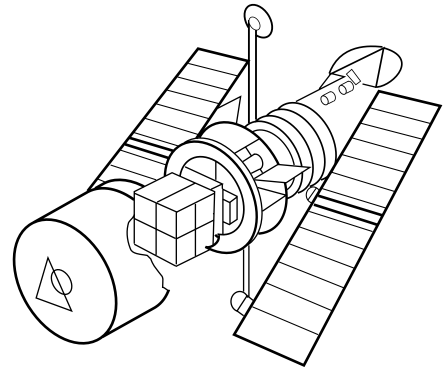
Refracting Telescope – First used by Galileo Galilei to discover the moons of Jupiter, the refracting telescope consists of curved pieces of glass that bend light into the eyepiece.

Advantages	Simple design and construction.
Disadvantages	Some light passing through the lens will be absorbed or distorted by the glass lens (aberration). Large telescopes are also impractical because larger glass lenses are too heavy and sag under their own weight, causing further distortion.
Largest refractor	1-meter, Yerkes Observatory, Wisconsin, USA.



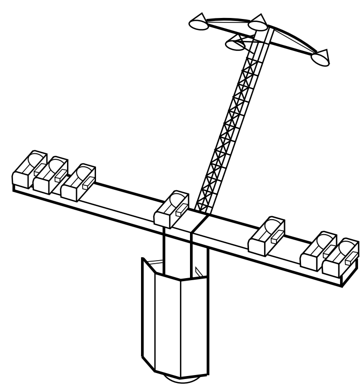
Reflecting Telescope – Invented by Isaac Newton. A curved mirror, instead of a curved glass lens, focuses the light.

Advantages	Mirrors can be made much lighter than glass lenses, allowing construction of larger telescopes with less image distortion.
Disadvantages	Large reflecting telescopes are ground based, which means they must be pointed up so that an observer must look through Earth's atmosphere to see the stars. The "twinkling" of stars as seen from Earth results in image distortion, and is caused by differences in air temperature and wind patterns.
Largest single-mirror reflector	6-meter, Mt. Pastukhov, Russia.
Largest multiple-mirror reflector	10-meter, Keck Observatory, Hawaii, USA.



Hubble Space Telescope – Launched into orbit around Earth in 1990, the 2.4-meter (7.87-foot) Hubble Space Telescope operates outside Earth's atmosphere and offers a clear, unobstructed view of the universe. Images of unsurpassed clarity and resolution from its cameras have allowed numerous new discoveries and breathtaking pictures.

Advantages	No atmospheric distortion.
Disadvantages	Space telescopes are limited in size and weight by the size of the space shuttle payload bay that launches them. Although the Hubble produces images unprecedented in clarity and resolution, there is a limit to its resolving power and light-gathering abilities due to the fixed diameter of its mirror.



Interferometers – Currently being designed and tested at two ground-based locations (the Palomar Observatory in California and the Keck Observatory in Hawaii), this class of telescope will eventually be launched into space in the program known as the Space Interferometry Mission (SIM). Interferometers work by combining light from two or more small and widely separated mirrors into one image. The image the interferometer produces is really a computer-enhanced read out of light interference patterns. This detailed look at a star allows scientists to detect very slight stellar movements and blocks out any incoming light from the star, allowing them to see even small, orbiting objects.

Advantages	Use of small but widely separated mirrors achieves a higher resolving power with very little weight in the telescope.
Disadvantages	Since only small mirrors are used, its light-gathering abilities are very limited. It cannot image extremely dim or faint objects.

Questions for Discussion

Star Classifications

1. Why must a star's absolute magnitude be used when plotting it on the H-R diagram? Why can't astronomers use the "apparent" brightness of a star in the sky?

2. Most stars in the universe are main-sequence stars. Describe the general relationship between the brightness of a main-sequence star and its temperature and color.

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3. Deep blue stars are quite rare. Even if they were born at the same rate as other stars in the main sequence, they would still be scarce and hard to find today. Why are there so few blue or massive stars today?

4. A certain cluster of stars is found to be missing all O- and B-class (bluish) stars. How can astronomers use this information to determine the approximate age of the star cluster?

5. What class of star is our own Sun? How much longer should it be around?

6. Throughout the life of a star, it changes from one type to another. The life cycle of a typical star starts in the main sequence. If it is much larger than our Sun, it may end its life in a cataclysmic supernova explosion. If it is not large enough to go supernova, it will become a red giant and finally end its life as a white dwarf. Write a story of an imaginary G-class star from its birth from a cloud of gas until its death. Include the approximate length of time in each stage of the star's life, where possible, and its color and temperature.

Tools of the Trade

1. Why couldn't scientists just make larger and larger reflector or refractor telescopes until they could image planets orbiting other stars?

2. Why do we want to make astronomical observations from space?

3. Why will Earth-orbiting interferometers need to focus on objects that are relatively close to Earth, as compared to those studied by the Hubble Space Telescope or large Earth-based reflecting telescopes?

Planetary Types

1. What major differences between the inner four planets and the outer five planets can you determine by interpreting the graphs?

2. What general relationships can you find between a planet's distance from the Sun and its orbital period and rotation?

3. Given that liquid water's density is 1 g/cm^3 (1.0361 lb/in^3), make a comparison of the densities of the nine planets. How are the first four different from the next four in density? The first four planets are called the inner planets. They are also known as the terrestrial, Earth-like, or rocky planets. The next four planets are called the gaseous giants. Does Pluto seem to belong to the gaseous giants? What could explain this anomaly?

4. An astronomer notices a wobble in a G-class star (similar to our own Sun). The wobble has a period of 20 Earth years. How far from the star should the astronomer look to find a planet, assuming that the star system behaves like our own solar system?

5. Some astronomers describe Earth's unique environment as the "Goldilocks" zone. It's not too hot and not too cold — but just right — to sustain life. Earth is also at just the correct distance from the Sun to allow liquid water to exist over much of its surface. Water has the highest capacity of any common natural substance to absorb and retain heat, and it evenly distributes that energy around Earth. What roles does water play in sustaining life on Earth? (Think about the chemical, biological, and physical roles.)

Poster Interpretation

1. Only two elements, hydrogen and helium, were present at the formation of the universe. How is it that there are now 92 naturally occurring elements?

2. Heat energy released during nuclear fusion causes matter to expand and push outward, while gravity causes matter to contract and condense. Describe how changes in these two forces affect the life of a star from birth to death and then to regeneration.

3. Predict how the proportion of lighter elements compared to heavy elements in our galaxy will change in the next few billion years.

4. Explain how and why star formation is a process that occurs in a repeating cycle.

The Origins Program and Other Missions

The National Aeronautics and Space Administration (NASA)

One of the greatest questions facing humankind is, “Are we alone?” For centuries, people have wondered if there are worlds among the stars in the sky. Over the last 100 years, astronomers have trained larger and larger telescopes on those stars. However, it was not until 1996 that scientists were able to verify the existence of a few large planets around select stars. Those planets are several times larger than the largest planet in our own solar system, Jupiter. Today, we do not know how common planets are in the universe. Are there smaller planets out there, similar in size to Earth? And, could any of them support life?

NASA is committed to addressing these and other fundamental questions about our place in the universe. It has begun the Origins Program to coordinate the development of new technologies that will enable us to explore the processes of how galaxies, stars, and planets, and even life form, in the hopes of gaining clues to how we might have gotten here.

For this purpose, NASA has laid out a clear roadmap of technologies and missions that leads well into the first half of the 21st century. The Hubble Space Telescope represents the first element in this set of tools developed by NASA’s Origins Program. Its exciting new images (some shown on the front of this poster) show how stars form out of large clouds of interstellar dust and gas.

However, to answer the questions posed by the Origins Program, we will need observatories that exceed the already tremendous capabilities of the Hubble Space Telescope by more than a thousandfold. NASA’s technology roadmap addresses this need for vastly increased sensitivity and resolution so that astronomers might see fainter and fainter objects with more and more details. This will require several breakthroughs in technology. NASA has decided to make a technique, known as interferometry, a key technology for the missions in the Origins Program.

Using interferometry, astronomers will be able to link small telescopes together into a much more capable instrument. For example, several small telescopes can be placed at specific locations in an area covering many kilometers; this arrangement acts as if it were one large telescope with a mirror the size of that entire area.

Like any new technology, interferometry needs to be developed in steps to live up to its full potential. Through the Jet Propulsion Laboratory (JPL) of the California Institute of Technology, NASA has started work on the following five programs to develop optical interferometry:

- The Palomar Testbed interferometer is currently in operation at the site of the historic 200-inch Hale telescope at Mt. Palomar in southern California. This dual-star interferometer measures the angular separation between two stars very accurately and has already produced valuable scientific results. The technology developed at Palomar directly leads to the next project.
- The Keck Interferometer will combine the two 10-meter (32.8-foot) Keck telescopes on top of Mauna Kea on the island of Hawaii and proposes to add four additional smaller outrigger telescopes. After its completion in 2002, the Keck Interferometer will be the most sensitive infrared interferometer in the world.
- Deep Space 3 (DS3) is a space-based mission that will demonstrate a key step in the development of interferometry in space. For the first time, DS3 will demonstrate how to combine light from telescopes on separate spacecraft into one measurement. This requires that a cluster of several spacecraft will be able to fly in precise formation and that all elements in this array can keep their position with high accuracy.
- The Space Interferometry Mission (SIM) will be the first optical long-baseline interferometer in space. Targeted for launch in 2005, SIM will measure the position of stars several hundred times more precisely than any other mission. Therefore, SIM will be able to detect planets as small as Earth in the habitable zone around nearby stars.
- The most ambitious project in this series is Terrestrial Planet Finder (TPF), which will take “family portraits” of planetary systems. Such a snapshot image of a solar system will show all planets at once, and TPF will also be able to characterize the atmosphere of these planets by taking a spectrum of the reflected light of the planets. Such a spectrum will carry the “fingerprint” of the planet’s atmosphere, and it will allow scientists to determine whether there is oxygen or other gases, such as methane, that are indicative of biological activity.

For more information, visit the Origins World Wide Web site at — http://origins.jpl.nasa.gov/