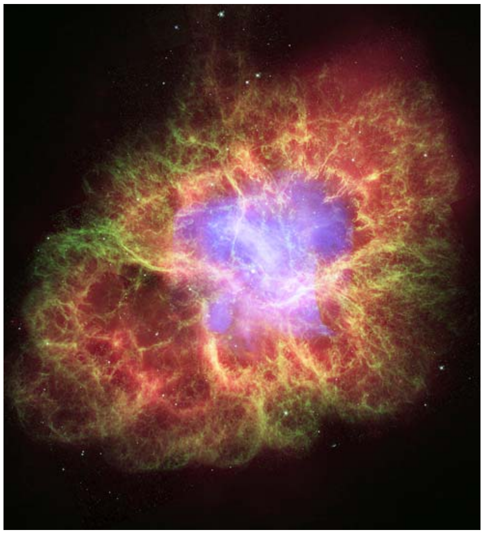
Chapter 9: The Life of a Star



The Crab Nebula and Pulsar Composite Image (Chandra, Hubble, Spitzer)

Introduction

Massive stars explode when they die, releasing as much light as an entire galaxy of stars. Such an explosion is called a *supernova*. It can catapult a star from obscurity to spectacular prominence in the night sky. A supernova that occurred in the year 1006 (SN 1006) shone so brightly that objects could be seen by its light for weeks. A Muslim astrologer, Ali ibn Ridwan of Cairo, recorded the event. So did a monk named Hepidannus, of St. Gall, Switzerland. The records of these two men locate SN 1006 in the direction of the constellation Lupus in the Southern Hemisphere. Japanese and Chinese sources more precisely locate the supernova near kappa Lupi and one degree west of beta Lupi. It was the brightest star observed in all of recorded history. It was probably visible for three months during daylight, and only after three years did it fade below naked-eye visibility at night. The remnant left behind from the explosion has a low luminosity and large size, and is the faintest remnant of the five well-established historical supernovae seen during the last one thousand years. The remnant emits in the radio and X-ray bands and is thought to be 2300 light-years away.

On July 4, 1054, Chinese and Japanese astronomers recorded a bright star in the constellation Taurus which had not been visible before. At maximum brightness it was comparable to Jupiter, and remained visible to the unaided eye for 653 days in the night sky. No definite historical accounts of SN 1054 have come to light in Europe. However, it seems to have been observed and recorded in the rock art of the American southwest. An unusual picture exists in Chaco Canyon, New Mexico, painted on a rock panel with red hematite. The picture depicts a crescent shape not seen elsewhere in the canyon and which is clearly associated with a “bright” star. The star is stylistically unlike the typical Pueblo stellar representations. The rock panel is located in a Sun-watching shrine. It seems likely that the Sun-priest, whose duty it was to observe the daily sunrise, was struck by the spectacular association of the waning crescent Moon and the bright supernova and recorded it on the spot. On July 4, 1054, the crescent Moon would have been in the direction of Taurus. Representations of the same conjunction of a crescent moon and a bright star have been found at several other sites from Texas to California. The remnant left behind by SN 1054 is the Crab Nebula, and is a strong radio source known as Taurus A. In the center is a rapidly rotating pulsar with a period of 33 milliseconds.

On the evening of November 11, 1572, as Tycho Brahe was returning home from his chemistry lab, he saw a bright, unfamiliar star in the constellation of Cassiopeia. He hurried to get his sextant, and measured the distance of the star from the well-known stars in Cassiopeia. He made hurried notes as to its magnitude, color, and other characteristics. After several nights of observation, Tycho determined that it had no motion and was therefore a fixed star. It was more brilliant than Sirius and probably equal to Venus at its brightest. The star remained visible for seventeen months, until March 1574. Tycho compiled his observations and notes about the new star, and had them published. *De Novâ Stellâ* was his first publication and established his reputation as a scientist and scholar. Tycho's observations of SN 1572 were the beginning of his career as an astronomer. Both the supernova of 1054 and Tycho's supernova of 1572 were visible in daylight to anyone who knew they existed; however, neither was so bright as to attract the attention of the untrained eye.

In October 1604, a supernova appeared in Ophiuchus. The star became as bright as Jupiter, then faded from naked-eye visibility a year later. The most complete account of the supernova was given by Johannes Kepler. The optical remnant of SN 1604, seen as little patches of wispy nebulosity, was not detected until 1943.

SN 1987A was the first naked-eye supernova since 1604, and occurred in the Large Magellanic Cloud, approximately 160,000 light-years away. For the first time, Earth-bound astronomers had the technology and telescopes to observe the cataclysmic demise of a star across the entire electromagnetic spectrum. The event was noticed three months before maximum brightness, allowing the scientific community to determine if the explosion corresponded to predicted theories of violent gravitational collapse. SN 1987A peaked at 3rd magnitude three months after exploding and now, more than ten years later, has faded to a magnitude of +20. Studies are still being conducted on the gases shed and stellar winds produced during the stages before final collapse, and on the rapidly expanding remnant itself. The results will increase our knowledge of how a supernova produces and disperses elements into the interstellar medium.

Supernovae have an important role in the composition of matter. They are sites of nucleosynthesis, the production of new elements by nuclear fusion. These elements are thrown into the surrounding space and eventually become incorporated into other stars. Our own Solar System contains traces of supernovae that exploded before the Sun and planets formed. All elements on Earth, such as the iron found in hemoglobin, calcium in teeth, and the gold and silver that become jewelry, were originally manufactured in the cores of stars.

The red supergiant stage, which precedes a supernova explosion, may last for 100,000 years. Even though there are several supernova candidates in the galaxy, it is hard to tell how far any particular star is along the path to destruction. One such candidate is Betelgeuse, a red supergiant in the right shoulder of Orion that is 300 times larger than the Sun. It is surrounded by faint shells of dust which were apparently ejected from the star 50,000 to 100,000 years ago. Because the supergiant stage probably lasts only about 100,000 years, Betelgeuse may be quite close to the supernova explosion that will end its life. It may happen tomorrow or in 50,000 years. Since Betelgeuse is 410 light-years away, it will take that long for the information to reach us. Maybe it has happened already and we don't yet know. A supernova so close to Earth would create an extraordinary spectacle in the sky, visible even during the day and outshining every other star.

> To access a set of activities, materials, and resources on stellar evolution:
> *Stellar Evolution* at http://chandra.harvard.edu/edu/formal/index.html

Investigation 9.1: The Continuous Spectrum

Your instructor will provide a large continuous spectrum. How many colors are visible? Indicate the color boundaries. The wavelengths you are observing range from approximately 4000 to 7000Å. Measure the entire length of the spectrum in centimeters and determine the scale of your spectrum in Å /cm. Measure the length of each color and determine how many angstroms to which they correspond. Do your answers agree with the accepted values in Table 8.1? If not, what might be some reasons why? Is radiation being emitted that is not part of the visible spectrum? If so, what type? Where would you place it on your spectrum?

The Radiation Laws

All objects emit some type of electromagnetic radiation. The radiation laws describe both the amount and the wavelengths of radiation emitted by an object, which depend only upon its temperature. Since there is no such thing as a perfect reflector, all objects absorb some type of radiation. That radiation must then be emitted, or the object's temperature would continuously increase. Not all objects absorb or emit energy in the same way: some are more reflective or have a greater capacity for absorption. Some also transmit various wavelengths with their corresponding amounts of energy. A theoretical model, called a *black body*, is defined as the perfect absorber and radiator. Black bodies do not reflect any radiation, but rather absorb all radiation that falls on them and then radiate it all away. Stellar atmospheres are good approximations of black bodies. They absorb all the radiation rising from the core, and then emit the radiation into the surrounding space. Stars, like hypothetical black bodies, follow the three radiation laws: *Planck's law*, *Wien's law*, and *Stefan-Boltzmann's law.*

Black body radiation is thermal radiation emitted from a black body at a particular temperature. When an object is heated until it glows, it emits all wavelengths, or colors, of the visible spectrum. However, there is always one dominant, or peak, wavelength emitted that depends upon the temperature of the object. An object heated to 3000K emits radiation whose peak wavelength falls in the infared or near-infrared part of the spectrum. A 6000K object has a maximum wavelength output in the yellow; 12,000K is greenish, and 24,000K is in the ultraviolet or near-ultraviolet region of the spectrum. At lower or higher temperatures, the maximum wavelength output falls outside the visible spectrum. Therefore, the temperature of an object determines the dominant wavelength being radiated, which corresponds to a particular color. The continuous radiation from a star does not follow theoretical black body radiation exactly; however, it is similar enough to apply the black body radiation laws.

Planck's law describes the shape of the radiation curve of a "perfect radiator," which is represented graphically below in Figure 9.1. In analyzing the graph, the three major points of this law become apparent:

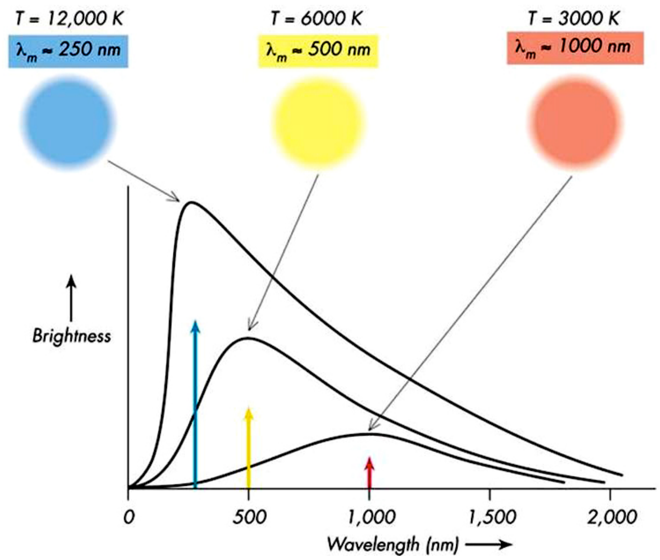


Figure 9.1

1. Any black body emits energy at every wavelength but not in the same proportions.
2. A hotter body produces more energy at every wavelength than a cooler body of the same radius and mass.
3. The hotter the body, the shorter the frequency of the dominant wavelength emitted; color depends on temperature.

Wien's law is simply a mathematical statement of point #3 of Planck's law. From the graph in Figure 9.1, a 3000K object produces a maximum wavelength peak at about 9500Å, and a 6000K object peaks at about 5000Å. Therefore, Wien determined that

$$\lambda_{max} = \frac{2.9 \times 10^7}{T}$$

where T is the temperature in kelvin, λ is the wavelength of maximum output in angstroms, and 2.9×10^7 is Wien's displacement law constant in angstroms. (Note: A *constant* is a number which represents the proportionality between two different units. In the above relationship it allows temperature in kelvin to be turned into the equivalent wavelength in angstroms.)

Astronomers can determine the maximum wavelength output by using an instrument called a spectrophotometer, which measures the intensity of all the wavelengths of radiation emitted by a star. The maximum intensity is then put into Wien's relationship to calculate the temperature of the star.

Stefan-Boltzmann's law is also easily understood by looking at Figure 9.1. The total energy emitted by a star at a specific temperature, such as 24000K, is equal to the area under the radiation curve for that temperature. In mathematical terms, the following relationship gives the energy emitted per unit area of body surface:

$$E = \sigma\, T_{eff}^{\;4}$$

where T_{eff} is the effective temperature in Kelvins; E is the energy per unit surface area in erg/cm^2; σ is the Stefan-Boltzmann constant, equal to 5.70 x 10^{-5} erg/cm^{-2}sec^{-1}K^{-4}. (An *erg* is a metric unit used for smaller amounts of energy than a Joule.)

The *effective temperature* is the best measure of the actual temperature of the gases in a star's outer layers. The effective temperature of a star is equal to the temperature of a black body having the same radius and radiating the same amount of energy as the star. Therefore, T_{eff} can also be stated as a function of the radius and power output as follows to calculate the total output of a star:

$$L = 4\pi R^2 E = 4\pi R^2 \sigma\, T_{eff}$$

where L is the luminosity, or total energy output per second; R is the radius of the star; T_{eff} is the effective temperature in Kelvin, and $4\pi R^2$ is equal to the area.

The Sun emits the entire spectrum of electromagnetic radiation (EMR), from X-rays through radio waves. Nearly 100% of the radiation is in the infrared, visible, and near ultraviolet range; shorter wavelength ultraviolet, X-ray, and radio bands comprise a small fraction of the total. The photosphere is the "visible" surface that we see, and it has a surface temperature of 5770K. This temperature corresponds to a wavelength of ~5500Å, which lies in the yellow-green part of the visible spectrum. Sirius has a surface temperature of ~12,000K and also emits the entire range of EMR. With its higher temperature, Sirius will emit more of every single wavelength than the Sun. Its maximum wavelength output will be of a high frequency and is in the blue end of the spectrum. The same overall result holds for all stars that are the same size or larger than the Sun, and have a higher temperature.

Stellar Classification and the Hertzsprung-Russell Diagram

Stars are classified by temperature or spectral type from hottest to coolest as follows:

O B A F G K M R N S

(Sometimes R and N stars are grouped together into spectral type C.) These categories are further subdivided into subclasses from hottest (0) to coolest (9). The hottest B stars are B0 and the coolest are B9, followed by spectral type A0. Each major spectral classification is characterized by its own unique spectra. Stars of spectral type G, like our Sun, have an effective surface temperature of 5000 to 6000K, with a maximum peak output that falls in the yellowish-green part of the spectrum, and have the strongest double calcium lines of any spectral type. Spectral lines can show different characteristics within the same spectral type, and so a second type of classification system for stars was devised using luminosity. The differences in spectral lines among stars having the same spectral type is a function of the radius of the star, which results in different luminosities. *Luminosity* (L) is related to the absolute magnitude of a star, and is equal to the total outflow of power. Two stars with similar effective temperatures but greatly different luminosities must differ in size: they belong to different luminosity classes within that spectral type, as determined from their spectra. The Sun is assigned the value of one solar luminosity. Stellar luminosities range from one million times more luminous than the Sun, to one ten-thousandth of the luminosity of the Sun.

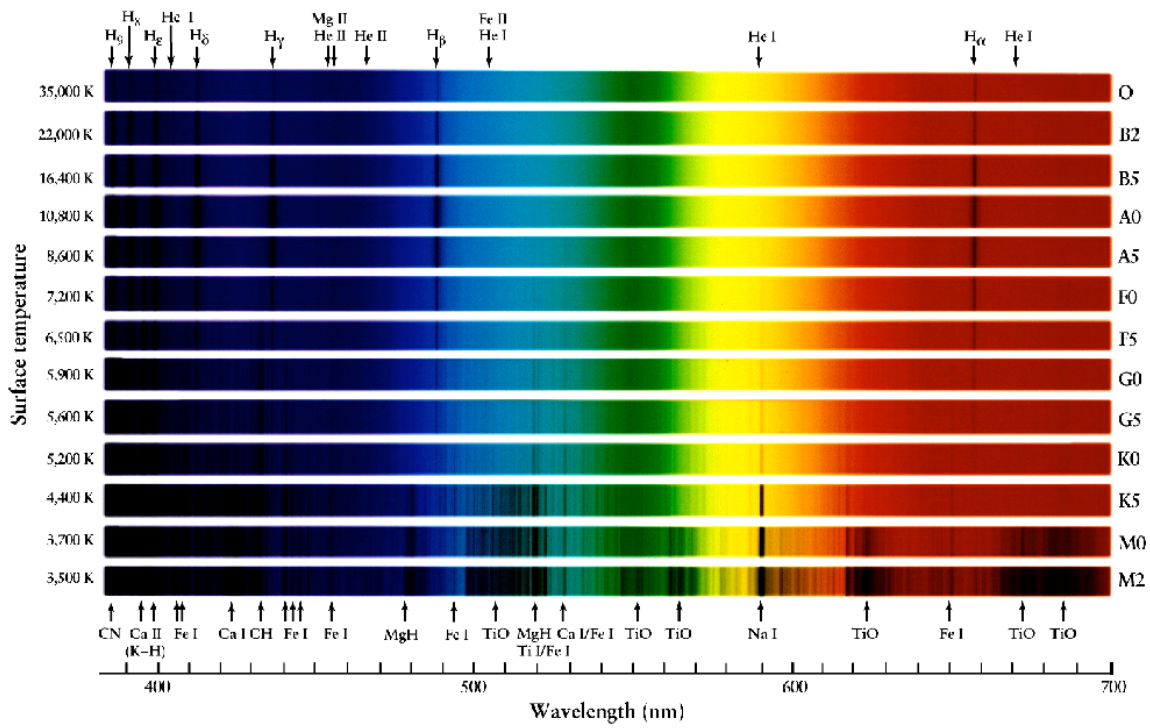


Figure 9.2 Stellar Spectra

The light sources and spectrum tubes you studied with a spectroscope produced bright emission lines. This is because there were no thick layers of atmosphere to interfere with the emission lines. Stars, unlike tubes of elemental gases, produce *absorption lines* because the outermost layers absorb radiation from the core. Because a star is like a black body, it absorbs the radiation and then emits it into the surrounding space. This radiation is emitted over a range of wavelengths, so we see dark lines, called absorption lines, where the radiation is "missing." All stars have a similar basic chemical composition; differences between spectral types are due only to the different effective temperatures. Hydrogen produces dominant spectral lines in stars with an effective temperature near 10,000K. At this temperature, electrons of the hydrogen atoms are becoming excited and then undergoing de-excitation and transiting down to the second energy level, or Balmer line, giving off photons in the visible part of the spectrum. At hotter temperatures, most of the hydrogen is ionized—the electrons have been stripped away. There are fewer intact hydrogen atoms to produce the characteristic spectral lines. The few hydrogen atoms that have managed to retain their single electron are mostly in such highly excited states that their spectral lines are invisible, since they fall back down to the the Lyman line (ground state) and emit photons in the ultraviolet part of the spectrum. Only the few neutral atoms of hydrogen that manage to retain their electrons and are not in a highly excited state can absorb and re-emit visible radiation. Since there are fewer electrons that can fall back down to the Balmer line, there are fewer photons emitted in the visible part of the spectrum and the absorption lines are weaker than in cooler stars.

Cooler stars, such as the Sun (surface temperature of 5770K), are not hot enough to excite the hydrogen atoms. The electrons remain mostly in the ground state and produce only very faint absorption lines. Cool red stars with surface temperatures of a few thousand kelvins show extremely weak hydrogen lines. Their spectra contain many absorption lines produced by molecules rather than elements, as they are so cool that even molecules can remain intact. Although stellar spectra vary widely in the strength of hydrogen absorption lines, it is due to the effective surface temperature of the individual star, and not a difference in the amount of hydrogen present (see Figure 9.2).

When stars are plotted on a graph of luminosity or absolute magnitude versus spectral classification (temperature), the results reveal the evolutionary stages of the stars. This graph is called the Hertzsprung-Russell, or H-R, diagram. You have seen that the temperature is easily obtained by determining the wavelength of radiation of greatest intensity from spectrophotometry. Absolute magnitude is defined as the brightness of a star at a distance of 10 parsecs from the Sun. The absolute magnitude can be obtained from a mathematical relationship called the *distance modulus*, a relationship involving apparent magnitude, absolute magnitude, and distance of a star. The apparent magnitude is determined visually, and if the star is close enough to determine its distance through parallax, the absolute magnitude can be derived from the following equation:

$$\mathbf{M = m - 5\log_{10} (r/10)}$$

where m is the apparent magnitude, M is the absolute magnitude, and r is the distance in parsecs.

If stars are too distant to measure their parallax, we must use other techniques, such as the period-luminosity relationship of Cepheid variable stars. With Cepheids, apparent and absolute magnitudes can be determined, and then the distance can be calculated with the distance modulus.

In considering the H-R diagram above (Figure 9.3), notice that the distribution of stars is not random throughout the graph. The stars follow certain trends, and there are some places where no stars exist.

Starting at the upper left-hand corner and curving down to the lower right-hand corner is a band called the *main sequence*. 90% of all stars lie within the main sequence. These stars run from the hot and bright O and B stars at the top left-hand corner to the cool, dim K and M stars at the lower right-hand corner. Main sequence stars have a fairly steady rate of fusion of hydrogen going on in their cores. The Sun is a main sequence G2 star. At the top of the diagram is a band of stars that have a high luminosity but may be cool in temperature. In order for this relationship to occur, these stars must have a large surface area; these are the *red giants* and *supergiants*. In the lower left-hand corner runs a band of objects which are extremely hot with a low luminosity. These objects must be very small to have such a low luminosity. They are called *white dwarfs*, and are the end products of the collapse of stars with a mass similar to the Sun. White dwarfs, red giants, and supergiants represent different evolutionary stages in the life of a star. In main sequence stars, the force of radiation pressure pushing outward from the fusion process is balanced by the inward pull of gravitational forces. When hydrogen, the fuel for nuclear fires, begins to run out, the two forces become unbalanced. The star then begins a series of stages as it begins to die. We can see this process represented by stars outside the main sequence in the H-R diagram.

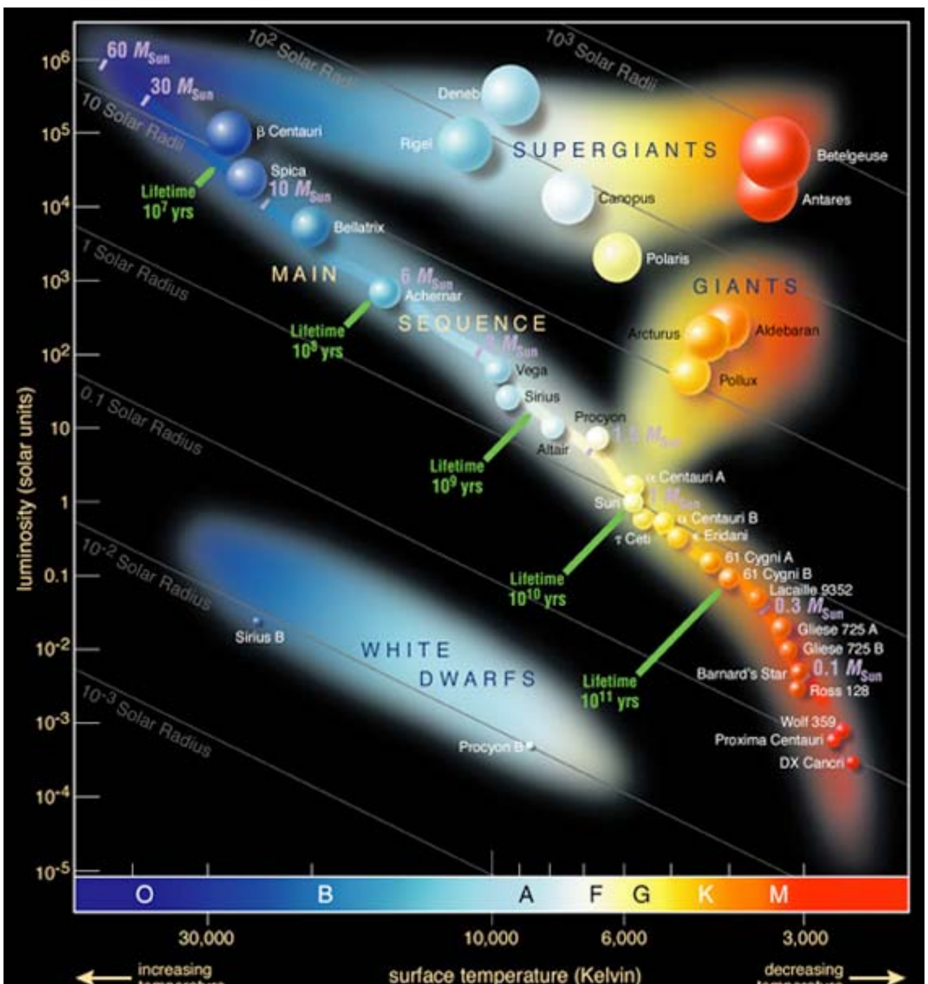


Figure 9.3 H-R Diagram

"The most original thinker of all..."

Antonia Caetana de Paiva Pereira Maury (1866-1952) was born in Cold Spring, New York. She was the granddaughter of John William Draper and niece of Henry Draper, both prominent physicians who were also noted amateur astronomers specializing in astrophotography. In fact, it was the stellar spectra work of Henry Draper which eventually led to Antonia's career at the Harvard College Observatory (HCO). Not long after graduating from Vassar in 1887 with honors in astronomy, physics, and math, Antonia enthusiastically accepted a position at the Observatory, where she worked on and off until 1935.

Antonia joined the HCO during the Henry Draper Memorial project, a monumental stellar classification project. Her intellect and education made her especially well-suited for the task of re-evaluating the new and greatly improved stellar spectra photographs. Maury independently established her own system for the classification of spectra. She reordered some of the original spectral classes to represent a sequence in temperature and decided that they were inadequate to describe the complexity of the spectral lines she saw. She therefore added a second "dimension" to the system-a letter which described the appearance of the spectral lines: `a' for wide and well-defined; `b' for hazy but relatively wide and same intensity as `a'; and `c' for spectra in which the H and "Orion lines" (now known to be due to helium) were narrow and sharply defined, while the calcium lines were more intense. She also had a class `ac' for stars having characteristics of both `a' and `c'. *The Henry Draper Catalogue* finally appeared in print in 1897, and in it Maury emphasized the importance of the `c characteristic,' which she firmly believed represented a fundamental property of the stars. This was due to different luminosity classes of the stars. Her work was later praised by Hertzsprung.

Marvelling at the vast expanse of the known universe, she wistfully philosophized, "But the human brain is greater yet, because it can comprehend it all."

-*"Antonia Maury"* in **Maria Mitchell's Famous Students**, by Dorrit Hoffleit.

Antonia Maury was the first to determine the period of the first spectroscopic binary star, Mizar-discovered by HCO Director E. C. Pickering in 1889. That same year Maury discovered the second spectroscopic binary, beta Lyrae. This type of star-whose duplicity is known through irregularities in its spectra-soon became her main interest in astronomy, and she would spend many years studying photographs of the stellar spectra of these stars. She not only was the first person to find the orbital periods of these double stars, but she also was the first person to compute their orbits. She devoted most of her attention to her favorite, and spectroscopically very complex star, beta Lyrae. According to astronomer Dr. Dorrit Hoffleit, Antonia Maury "was the most original thinker of all the women Pickering employed; but instead of encouraging her attempts at interpreting observations, he was only irritated by her independence and departure from assigned and expected routine."

Colonel John Herschel called Maury's work on spectroscopic binaries "one of the most notable advances in physical astronomy ever made." She was appointed Pickering Fellow for 1919–20 to aid in her spectroscopic work. After her official retirement from Harvard in 1935, she continued to visit the observatory yearly to check on observations of her final project, the enigmatic double star, beta Lyrae. In 1943, the American Astronomical Society awarded Antonia Maury the Cannon Prize for her work on stellar spectra.

Not only was Antonia Maury an accomplished astronomer, but she was also a dedicated naturalist, a recognized authority on birds, and a conservationist of historical sites and of natural resources.

Hertzsprung *and* Russell

In 1905 an amateur astronomer and photographer in Denmark, Ejnar Hertzsprung, studied the relationship between a star's color and its absolute brightness, or luminosity. He expressed color as a star's spectral class, and expressed luminosity as absolute magnitude (a notion he had invented), then plotted a graph of these variables for a large number of stars. He noticed that the vast majority of stars fall along a thin, slightly s-shaped line from upper left (bright and blue) to lower right (faint and red). Because he published his results in a popular photography magazine, rather than in a scientific journal, astronomers didn't notice his result.

Almost a decade later, in 1914, the American astronomer Henry Norris Russell drew essentially the same graph, and made essentially the same discovery-that most stars fall near a thin line in the graph. Hertzsprung's article was noticed soon after that, and it was clear that both had independently discovered the spectrum-luminosity relationship.

For a time, this relationship was known in the United States only as the *Russell diagram*. But to a young Dutch astronomer, Willem J. Luyten, who had studied under Hertzsprung at Leiden University, the spectrum-luminosity relationship was always the *Hertzsprung diagram*. It was not until "many years later," according to Luyten, that another Danish astronomer, Bengt Stromgren, convinced other astronomers to acknowledge Hertzsprung as well. As Luyten wrote in his autobiography:

> *We now know that Russell had actually written to Hertzsprung and admitted that Hertzsprung had the idea first, adding, "When I publish, I shall mention this," but when actually publishing, he carefully forgot about it. Russell always resented my referring to the diagram as the Hertzsprung diagram. In any case, the truth eventually prevailed and it is now know as the H-R Diagram, with the order in which the names are cited in conformity with the chronological order of invention.*

What we now call the Hertzsprung-Russell diagram, or simply the *H-R diagram*, is one of the basic tools of modern astronomy.

Core Activity 9.2: Plotting an H-R Diagram

The Hertzsprung-Russell diagram is a graph that plots a star's absolute magnitude versus its temperature (spectral class). Below are a list of 25 of the brightest stars and a list of 25 of the nearest stars. Set up a graph of an H-R diagram with an appropriate scale and plot the 50 stars, using different symbols or colors to differentiate the two lists on the diagram. Then answer the questions about the stars that you have plotted.

Table 9.1

SOME OF THE BRIGHTEST STARS*

	Star	Spectral Class	Absolute Magnitude		Star	Spectral Class	Absolute Magnitude
1.	The Sun	G2	4.8	14.	Spica (α Vir)	B1	-3.6
2.	Sirius (α CMa A)	A0	1.8	15.	Aldebaran (α Tau A)	K5	-0.5
3.	Canopus (α Car)	A9	-5.5	16.	Becrux (β Cru)	B0	-4.0
4.	Vega (α Lyr)	A0	0.6	17.	Fomalhaut (α PsA)	A3	1.8
5.	Arcturus (α Boo)	K2	-0.1	18.	α Cen B	K1	5.6
6.	α Cen A	G2	4.5	19.	Pollux (β Gem)	K0	1.2
7.	Rigel (β Ori)	B8	-6.7	20.	Regulus (α Leo A)	B7	-0.6
8.	Capella (α AurA,B)	G6+G2	-0.3	21.	Adhara (ε CMa A)	B2	-4.2
9.	Achernar (α Eri)	B3	-2.8	22.	Shaula (λ Sco)	B1	-5.1
10.	Procyon (α CMi A)	F5	2.7	23.	Bellatrix (γ Ori)	B2	-2.8
11.	Agena (β Cen A,B)	B1	-5.5	24.	Castor (α Gem A,B)	A2	0.6
12.	Acrux (α Cru A)	B0	-4.3	25.	Alnath (β Tau)	B7	-1.4
13.	Altair (α Aql)	A7	2.3				

* Absolute magnitudes of all stars except the Sun were calculated from parallax measurements and apparent magnitude (Hp) measurements taken from The European Space Agency, et al., *The Hipparcos and Tycho Catalogues* (17 Vols.), Noordwijk, The Netherlands: ESA Publications Division, 1997. ISBN 929092-399-7 (Vols. 1–17).

Table 9.2

SOME NEARBY STARS*

	Star	Spectral Class	Absolute Magnitude
1.	The Sun	G2	4.8
2.	α Cen C	M5	15.2
3.	α Cen A	G2	4.5
4.	α Cen B	K1	5.6
5.	Barnard's star	M5	13.2
6.	70 Oph A	K0	5.6
7.	Sirius A (α CMa A)	A0	1.8
8.	V1216 Sgr	M4	13.0
9.	ε Eri	K2	6.3
10.	HIP 114046	M0	9.8
11.	FI Vir	M4	13.4
12.	V1803 Cyg	K5	7.7
13.	Procyon (α CMi A)	F5	2.7
14.	61 Cyg B	K7	8.4
15.	HIP 91772	M3	12.3
16.	GX And	M1	10.4
17.	HIP 91768	M3	11.2
18.	ε Ind	K4	7.0
19.	τ Cet	G8	5.8
20.	YZ Cet	M4	14.1
21.	Luyten's star	M3	11.9
22.	Kapteyn's star	M1	11.0
23.	AX Mic	K7	8.8
24.	Kruger 60 A	M3	11.6
25.	V577 Mon	M4	12.9

* Absolute magnitudes of all stars except the Sun were calculated from parallax measurements and apparent magnitude (Hp) measurements taken from The European Space Agency, et al., *The Hipparcos and Tycho Catalogues* (17 Vols.), Noordwijk, The Netherlands: ESA Publications Division, 1997. ISBN 929092-399-7 (Vols. 1–17).

QUESTIONS ABOUT THE H-R DIAGRAM GRAPH:

1. Label the following branches of the H-R diagram: Main Sequence, Giant, Supergiant, White Dwarf. Calculate the percentage of stars that occupy each branch, and briefly describe, from the information on the two axes, the types of stars that occupy each branch.
2. Which stars are similar in magnitude and spectral class to the Sun?
3. Which list (brightest or nearest) gives the more typical example of the star population of the Milky Way Galaxy? Explain your reasoning.
4. Write a brief statement describing the relationship between absolute magnitude and stellar classification (temperature) of main sequence stars.
5. Does the above relationship hold for stars occupying the other branches of the H-R diagram?
6. Can you describe any relationships between absolute magnitude and stellar classification for any of the non-main sequence branches? Explain why you can or cannot.
7. Would you expect the same percentage of stars to occupy each branch of the diagram if all stars within the Milky Way Galaxy were plotted? Explain why or why not.
8. Why are there places on the diagram where no stars exist?
9. The next activity involves plotting variable stars on the same H-R diagram that you have constructed. Where do you think stars that vary in magnitude will end up on the diagram? Will they occupy one or more of the existing branches? Some of the empty places? Both? Write down your prediction, along with your reasoning. How would you plot a star that changes in brightness? What exactly is changing in these stars besides brightness?

Core Activity 9.3a: Variable Stars and the H-R Diagram

Plot the variable stars in Table 9.3a below. To see the relationship among main sequence stars, giants and white dwarfs to the variable stars, plot them on the same graph you made in 9.2. Variables have two absolute magnitudes, one at maximum and one at minimum. They also have enough variation to change spectral classes.

Table 9.3a

Star	Type*	Distance[1] (parsecs)	Magnitude[2] (apparent)	Spectral Class	Absolute Magnitude (M)
RT Aur	C	480	5.0–5.8	F4–G1	-3.4 / -2.6
delta Cep	C	300	3.5–4.4	F5-G1	-3.9 / -3.0
rho Cas	SR	3600	4.1–6.2	F8–K0	-8.7 / -6.6
T Cas	M	1700	7.9–11.9	M6–M9	-3.2 / +0.8
TU Cas	C	1100	6.9–8.2	F3–F5	-3.3 / -2.0
UU Aur	SR	560	7.8–10.0	C5–C7	-0.9 / +1.3
chi Cyg	M	106	5.2–13.4	S6–S10	+0.0/ +8.2
X Cyg	C	680	5.9–6.9	F7–G8	-3.3 / -2.3
T Cep	M	210	6.0–10.3	M5–M8	-0.6 / +3.7
Y Oph	C	880	5.9–6.4	F8–G3	-3.8 / -3.3
RS Boo	RR	1300	9.7–10.8	A7–F5	-0.9 / +0.2
VX Her	RR	2100	9.9–11.2	A4–F4	-1.7 / -0.4

*Variable star types (see page 152).

[1] Distances were calculated from parallax measurements taken from the European Space Agency, *et al.*, *The Hipparcos and Tycho Catalogues* (17 Vols.), Noordwijk, The Netherlands: ESA Publications Division, 1997. ISBN 92-9092-399-7 (Vols. 1–17).

[2] Apparent magnitudes taken from the 3rd and 4th editions of the *General Catalogue of Variable Stars*. Those of M-type variable stars are mean apparent magnitudes of maxima and minima.

1. Are the variables located on the H-R diagram where you expected them to be?
2. What are the differences?
3. The parallaxes of some of these variable stars are less than 0.001 arcsecond. The accuracy of the HIPPARCOS parallaxes is only 0.001 arcsecond, on average. How accurate will these absolute magnitudes be?

Core Activity 9.3b: Variable Stars and the H-R Diagram

Plot the variable stars in Table 9.3b below. To see the relationship among main sequence stars, giants, and white dwarfs to the variable stars, plot them on the same graph you made in 9.2. Variables have two apparent magnitudes, one at maximum and one at minimum. Use the distance modulus to calculate the absolute magnitudes from the apparent magnitudes. The parallax measurements have to be converted to parsecs. The distance in parsecs is the reciprocal of the parallax. They also have enough variation to change spectral classes.

Distance modulus: $M = m - 5\log_{10}(r/10)$

Table 9.3b

Star	Type*	Parallax[1]	Distance (parsecs)	Magnitude[2] (apparent)	Spectral Class	Absolute Magnitude (M)
RT Aur	C	0.00209		5.0–5.8	F4–G1	
delta Cep	C	0.00332		3.5–4.4	F5–G1	
rho Cas	SR	0.00028		4.1–6.2	F8–K0	
T Cas	M	0.00059		7.9–11.9	M6–M9	
TU Cas	C	0.00091		6.9–8.2	F3–F5	
UU Aur	SR	0.00180		7.8–10.0	C5–C7	
chi Cyg	M	0.00943		5.2–13.4	S6–S10	
X Cyg	C	0.00147		5.9–6.9	F7–G8	
T Cep	M	0.00476		6.0–10.3	M5–M8	
Y Oph	C	0.00114		5.9–6.4	F8–G3	
RS Boo	RR	0.00077		9.7–10.8	A7–F5	
VX Her	RR	0.00047		9.9–11.2	A4–F4	

*Variable star types (see page 152).

[1] Parallax measurements were taken from the European Space Agency, *et al.*, *The Hipparcos and Tycho Catalogues* (17 Vols.), Noordwijk, The Netherlands: ESA Publications Division, 1997. ISBN 92-9092-399-7 (Vols. 1–17).

[2] Apparent magnitudes taken from the 3rd and 4th editions of the *General Catalogue of Variable Stars*. Those of M-type variable stars are mean apparent magnitudes of maxima and minima.

1. Are the variables located on the H-R diagram where you expected them to be?

2. What are the differences?

3. The parallaxes of some of these variable stars are less than 0.001 arcsecond. The accuracy of the HIPPARCOS parallaxes is only 0.001 arcsecond, on average. How accurate will these absolute magnitudes be?

*Variable star types listed in the preceding tables:

C - Cepheid. These stars pulsate with periods of 1 to 70 days. Cepheids obey the period-luminosity relation.

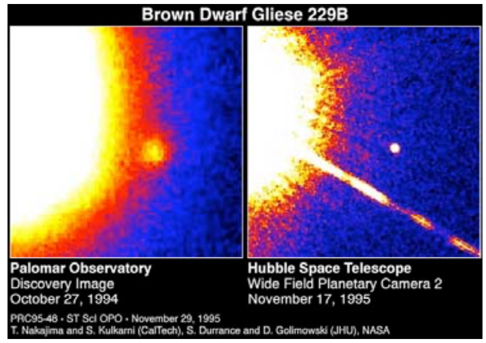
M - Mira. Red giant stars which pulsate with periods of 80 to 1000 days.

SR - Semiregular. These variables are giants and supergiants that show periodicity accompanied by intervals of irregular light variation. They have periods of 30 to 1000 days.

RR - RR Lyrae. Pulsating variable stars with periods of 0.05 to 1.2 days.

Planets or Stars?

There are two ways of detecting a planet, either directly by detecting radiation from the planet, or indirectly by observing the effect of the unseen planet on its parent star. Direct detection of planets is extremely difficult, as they are much dimmer than the stars they orbit. Direct observations have better results in the infrared band: peak emissions from planets occur in the infrared, and stars emit much less energy in the infrared band. Infrared imaging led to the discovery of the substellar brown dwarf Gliese 229B in orbit around the star Gliese 229.



Courtesy of Space Science telescope Institute/ NASA

The most common indirect methods track the motions of stars spectroscopically. If a star has a companion, then the star and companion orbit their shared center of mass, which causes perturbations, or disturbances, in the expected orbit of the star and/or Doppler shifts in spectral lines which can be detected.

The first planet found orbiting a Sun-like star is not at all what astronomers expected to find. The planet is orbiting 51 Pegasi, a 5.5-magnitude G-type star 40 light-years away, and very much like our Sun. The planet has half the mass of Jupiter with an orbital period of 4.2 days, so rapid that it must orbit at a distance of 7 million kilometers. Mercury orbits the Sun at a distance of 59 million kilometers. The existence of a giant planet so close to its star has created havoc with prevailing theories on the conditions necessary for planetary systems to form. The controversy surrounding 51 Pegasi and its companion is intense. However, the most recent evidence places the companion of 51 Pegasi in the planet category. The dividing line between brown dwarfs and planets is understood on a qualitative basis, but the actual dividing line between the two is unknown. A brown dwarf is by definition formed in the same manner as a star, and the dividing line between stars and brown dwarfs is mass. Brown dwarfs have an upper mass limit of around 75 to 80 Jupiters. However, the lower mass limit of brown dwarfs is not well understood. What is the amount of mass that represents the dividing line between brown dwarfs and planets? No one knows.

One likely planet is in a circular orbit approximately 2 AU's in radius around 47 Ursae Majoris. It is 75 million kilometers farther from 47 Ursae Majoris than Mars is from the Sun, and has a minimum mass of 2.3 Jupiters. One system which seems to be real was discovered by two radio astronomers. Two companion planets are orbiting a millisecond pulsar in Virgo named PSR 1257 + 12. The pulsar is 20 kilometers wide and 1600 light-years away. The inner planet orbits PSR 1257 + 12 at a distance slightly closer than Mercury and is 3.4 Earth masses, while the outer planet orbits slightly further than Mercury and is 2.8 Earth masses. 28 million kilometers separates the two planets; they are nearly twice as close to each other as Venus is to Earth. Since a pulsar has gone through a supernova explosion, any pre-existing planets would have been destroyed during the violent collapse. It is possible that a second generation of planets could have formed from the fierce wind of radiation from the pulsar. The wind would erode material from a companion star. Two millisecond pulsars have been caught in the act of vaporizing their companion stars, so PSR 1257 + 12 may have done the same. The planets would undoubtedly be hostile and barren.

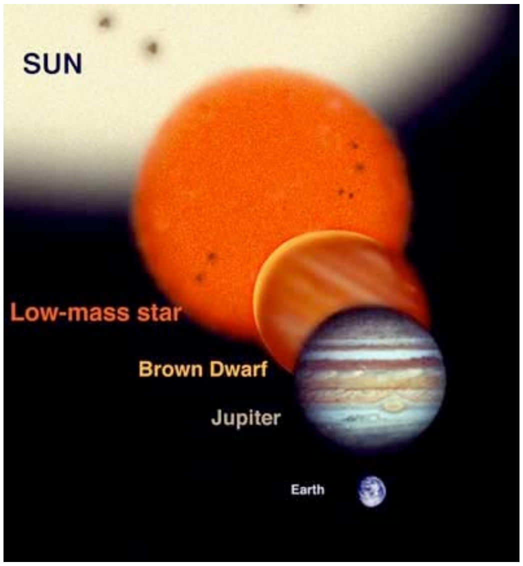
If other civilizations exist, they all share the same problems that the inhabitants of Earth face involving interplanetary or interstellar travel. One major obstacle is the mining of materials to support colonies on other planets or moons. The transportation of materials from the home planet would be cost-prohibitive and time-consuming. One possible solution being considered by NASA is the mining of basic materials from asteroids. Asteroids are being considered because of their variety of materials and favorable position for retrieval. Because of the long travel times to the main asteroid belt, the asteroids whose orbits bring them fairly close to Earth are being studied. The mining operations could dig and process the materials during the time spent traveling to the asteroid belt and back, and then the products could be recovered when the asteroid made its closest approach to Earth. The asteroid Apollo, for instance, crosses the orbit of Earth almost to Venus before returning to the asteroid belt. Apollo is one kilometer in diameter and has an orbit of 1.78 Earth years.

Combining information from spectral studies of asteroids and laboratory analyses of meteorites, investigations have indicated that near-Earth asteroids are rich in volatile materials such as water and organic materials, along with structural, precious, and strategic metals. The water could be decomposed into hydrogen and oxygen and used as rocket propellant. Samples in the form of carbonaceous chondrites and similar classes of meteorites which have impacted Earth indicate that their parent asteroids may have favorable mechanical properties. Some of these materials break up easily at very low pressures, much lower than that for most terrestrial materials. Some asteroid material can even be crushed by hand. Although other asteroids may be fundamentally tougher, impacts may have broken up their surfaces into thick layers of regolith (soil), and fractured the rocky material. This indicates that material from a near-Earth asteroid should be easily excavated and crushed by the same type of mechanical equipment already used for terrestrial mining.

A specific asteroid would have to be chosen before the mission could be planned. Physical properties of prospective candidates, such as mineral grades, mineral variability, specific mechanical characteristics of the asteroidal material, and orbital characteristics would have to be determined before a planned mission could proceed. The problems and expenses of a manned mission are huge. Such factors as long-term exposure to zero gravity, exposure to dangerous solar radiation, the design of controlled ecological life-support systems, and the deep-space transportation vehicle would all have to be considered. It is suspected that an asteroid mining mission will require human miners. Even on Earth many aspects of mining are not automated. Any type of automated or robotic asteroid mining project would have to work perfectly. Any small equipment failure would cause the entire mission to fail.

Although it might seem easier to move materials in zero gravity than on Earth, inertia, as well as the lack of gravity and weightlessness, are major problems to consider. One problem is that of holding mining and excavation tools to the surface of an asteroid. On Earth, equipment is held down solely by gravity.The property of inertia, Newton's second law, states that all objects remain at rest on in a constant straight-line motion unless a force is applied. This results in the problem of containing the excavated material, both the large and the small fragments. Rock-fracturing places an initial velocity on the broken material. On Earth, gravity quickly collects the broken rock. In weightlessness, the property of inertia would cause the broken rock to behave like out-of-control billiard balls, a potentially destructive game. The fine particles generated by rock-fracturing would obscure vision and clog equipment. Even though lunar mining would be cheaper and easier, the rich variety of materials in asteroids keeps them on the list of possible future mining sites.

SPACE TALK



More than 80% of all nearby stars are **red dwarfs**. Red dwarfs lie at the lower right- hand corner of the **H-R diagram**. These red, cool stars have a mass of one-half to one- tenth the mass of the Sun and are so cool that their **effective temperature** of ~2500K can be achieved in blast furnaces here on Earth. Larger main sequence stars like the Sun have different zones running from the core to the **photosphere**, or "surface." Surrounding the core is a **radiative zone** which carries the energy from the fusion process towards the surface; this zone is itself surrounded by a **convective zone** where the gases rise and fall like a boiling pot of water. Red dwarfs have no radiative zone; these stars are so cool that the entire interior is convective. If the Sun is thought of as being at full boil, a red dwarf would be at a gentle simmer.

Several years ago astronomers predicted the existence of another stellar-like object called a **brown dwarf**. Brown dwarfs are about the size of Jupiter, only 10 to 80 times more massive, up to about 8% of the Sun's mass. These objects flicker on and off by "burning" deuterium (heavy hydrogen) or other light elements; however, they are incapable of converting normal hydrogen into helium in sufficient quantities to shine steadily. Since brown dwarfs are not massive enough to have high enough temperatures and pressures in their cores to sustain a steady rate of fusion, they gradually fade throughout their lives. Their effective temperatures are thought to be ~740K. Brown dwarfs would also have fully convective interiors, but not with consistency—sort of an intermittent simmer. For galaxies, clusters, and superclusters to remain gravitationally bound and not fly apart, an adequate amount of mass is required. It is calculated that approximately 90% of the mass in the galaxy is not observable from Earth; all the objects we see constitute only ~10% of the required mass. Since the majority of main-sequence stars are dim red dwarfs, it is thought that enormous numbers of even dimmer brown dwarfs must exist, and some astronomers think that these brown dwarfs are significant contributors to the "missing mass" problem.

The first confirmed brown dwarf was discovered in 1995. Gliese 229B, which orbits a small spectral class M red star 19 light-years away in the direction of Canis Major. The search for brown dwarfs is difficult. It is hard to find objects with luminosities that are too dim, temperatures too cool, or colors too red for hydrogen-burning stars. Brown dwarfs also continually fade, and their luminosities, temperatures, and colors constantly change over time. To know if a candidate is actually a brown

30 Brown Dwarfs in Pleiades (Spitzer)

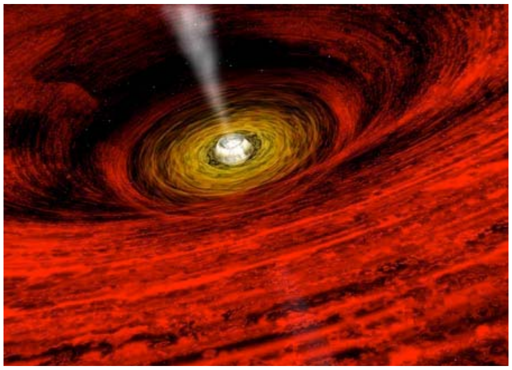
dwarf, either the age or the mass would have to be known. If a dim object has less than 7 to 8 percent of the Sun's mass, it cannot possibly be a star. Recent advances in technology have resulted in a growing catalog of brown dwarfs. The Spitzer infrared observatory has imaged several brown dwarfs in the Pleiades open cluster, a swarm of brown dwarfs has been imaged in the Orion Nebula, and even a binary system with two young brown dwarfs with masses of 50 and 25 times the mass of Jupiter have been detected orbiting each other at a distance of about 20 billion miles.

The mass of stars is difficult to determine. Mass can be directly measured only by applying Kepler's third law of planetary motion to stars in multiple star systems. A new method has been developed using **spectroscopy** and the element lithium. In normal stars, lithium is destroyed in nuclear collisions. Red dwarfs are fully convective and the lithium gets carried to the center and destroyed. Objects cooler than red dwarfs do not have a sufficiently high temperature to destroy lithium, so it becomes part of the atmosphere and can be detected by spectroscopic analysis. Gliese 229B has an absolute magnitude of ~+15.5, and therefore probably has a mass below the required 8% of the Sun's mass. The near-infrared spectrum shows the same molecules which exist in the clouds around Jupiter. This limits the effective temperature to less than 1000K, too low for a star. However, Gliese 229B is too close to its companion for a high-precision measurement of its mass, though new instruments being developed for HST might be able to handle the measurement. It is also too faint and too close to its brighter, primary star to apply Kepler's law or to determine the existence of lithium in its spectrum.

Brown dwarfs are not on the H-R diagram because they are not true stars and have no spectral classification. Main sequence stars similar to our Sun will evolve into red giants, sometimes throwing off planetary nebulae, and will eventually become white dwarfs. Stars in these two stages, red giants and white dwarfs, are located on the diagram because they have specific relationships between absolute magnitude and temperature (spectral types). The white dwarf stage will last for billions of years until these cores finish radiating away their energy and become cold chunks of carbon. The Sun will become a red giant in about five billion years, eventually becoming a white dwarf the size of the Earth. Larger stars which enter the red supergiant stage will go through a supernova explosion. The two end products of this explosion, **neutron stars** and **black holes**, are also not on the H-R diagram.

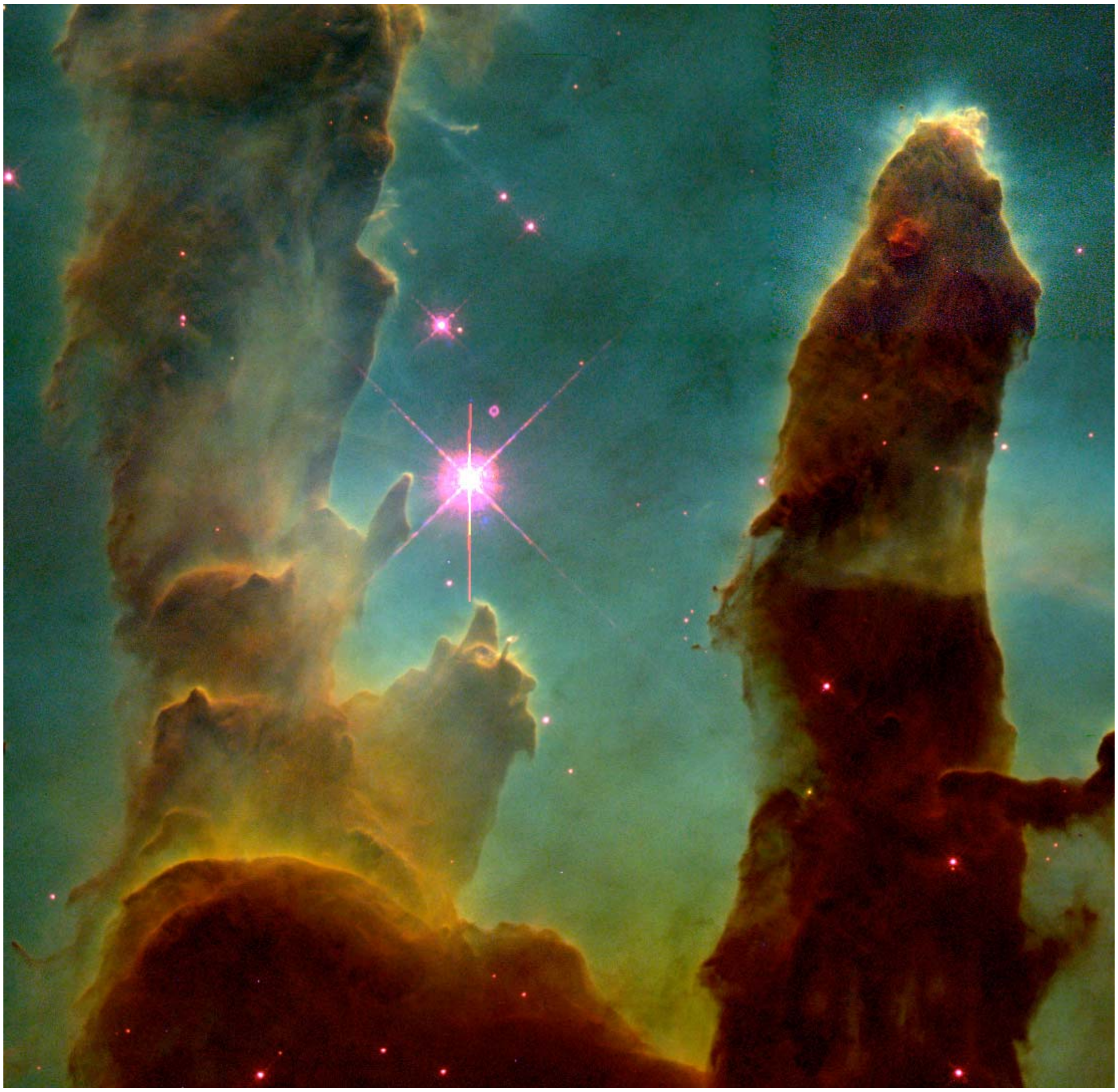
In white dwarfs, electron clouds are in contact with each other. The white dwarf does not collapse any further because its mass is not sufficient to overcome the repulsive force of the electron clouds. The white dwarf is then held in equilibrium by the opposing forces of **electron degeneracy pressure** and gravity. More massive stars can overcome the resistance of the electrons. During the collapse of these stars, the electrons are driven into the nuclei where they combine with protons and become neutrons. Neutrons are in contact with neutrons, and are held apart by the strong nuclear force—the strongest known force in the universe. Now the core is held in equilibrium by the opposing forces of **neutron degeneracy pressure** and gravity. The core can collapse no further and becomes a neutron star. A neutron star is so dense that a pinhead of its matter weighs more than a million tons. Some of these collapsed stars rotate and are called **pulsars**;

some of them, called millisecond pulsars, complete one cycle in just a few thousandths of a second.



Black Hole Illustration, April Hobart

In the most massive stars, even the strongest known force cannot withstand the force of gravity. Neutrons are pushed into neutrons, and nothing can stop the complete and total collapse of the star. It continues falling into itself until it becomes a **singularity**, a point of zero radius. The star becomes so dense, and the gravitational field so strong, that even light cannot escape. Black holes may cease to exist in the visible universe, but they leave behind clues to their existence. Such a large amount of matter confined in such a small space severely distorts the surrounding spacetime and any companion stars. Despite being the weakest of the four forces of nature, gravity overcomes the strongest forces, and defeats them all in a massive collapsing star.



1995 Hubble photo of the Eagle Nebula. The pillars are actually columns of cool interstellar hydrogen gas and dust that serve as incubators for new stars.