## ASTRONOMY

Chapter 17 ANALYZING STARLIGHT Chapter 18 THE STARS: A CELESTIAL CENSUS

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## A LIGHT-YEAR



Speed of light in space: $\sim 3 \times 10^{\wedge} 8$ meters/second Distance in a year: 86400 seconds/day * 365.25 days * $3 \times 10^{\wedge} 8 \mathrm{~m} / \mathrm{s}=$ $\sim 9.47 \times 10^{\wedge 15}$ meters

## LUMINOSITY

## 1000 Watt Stadium Light

 $1.5 \times 10^{\wedge} 5$ Lumens

Credit: https://www.mecreeled.com/football-stadium-lights-turning-many-lumens-need-light-football-field/

26 Watt Light bulb $1.7 \times 10^{\wedge} 3$ Lumens


Credit: 1000Bulbs.com

## FIGURE 17.3 - APPARENT BRIGHTNESS



Sagittarius Star Cloud. This image, which was taken by the Hubble Space Telescope, shows stars in the direction toward the center of the Milky Way Galaxy. The bright stars glitter like colored jewels on a black velvet background. The color of a star indicates its temperature. Blue-white stars are much hotter than the Sun, whereas red stars are cooler. On average, the stars in this field are at a distance of about 25,000 light-years (which means it takes light 25,000 years to traverse the distance from them to us) and the width of the field is about 13.3 light-years. (credit: Hubble Heritage Team (AURA/STScl/NASA))

Earliest recorded quantifications of the apparent brightness of stars were made by Hipparchus in 150 BCE. He also used parallax to determine the distance to the Sun and Moon.


Credit: Wikipedia

## MEASURING DISTANCE TO OBJECTS



## Parallax

$d$ (in parsecs) $=1 / p$ (in arcseconds)


## APPARENT BRIGHTNESS



Figure 17.2 Apparent Magnitudes of Well-Known Objects. The faintest magnitudes that can be detected by the unaided eye,
binoculars, and large telescopes are also shown.

## LIGHT FROM HOT OBJECTS



Heated metal glows red. If the metal could be heated to much higher temperatures, it would glow blue.

Idea used in thermometer guns, such as this one.

Color index involves measuring a star's light through three narrow light filters

- $360 \mathrm{~nm}-\mathrm{U}$ - ultraviolet light
- 420 nm - B - blue light
- $540 \mathrm{~nm}-\mathrm{V}$ - yellow or visible light

Use the differences, such as U-B or B-V to classify. Surface temperature can be determined by these measurements.

## FIGURE 5.8



Radiation Laws Illustrated. This graph shows in arbitrary units how many photons are given off at each wavelength for objects at four different temperatures. The wavelengths corresponding to visible light are shown by the colored bands. Note that at hotter temperatures, more energy (in the form of photons) is emitted at all wavelengths. The higher the temperature, the shorter the wavelength at which the peak amount of energy is radiated (this is known as Wien's law).

## SURFACE TEMPERATURE AND LUMINOSITY

Cooler objects are "redder", and hotter objects are "bluer."


A $15,000 \mathrm{~K}$ star is hundreds of times more luminous than a $3,000 \mathrm{~K}$ star, if they have the same size

TABLE 17.1

## Example Star Colors and Corresponding Approximate Temperatures

| Star Color | Approximate Temperature | Example |
| :--- | :--- | :--- |
| Blue | $25,000 \mathrm{~K}$ | Spica |
| White | $10,000 \mathrm{~K}$ | Vega |
| Yellow | 6000 K | Sun |
| Orange | 4000 K | Aldebaran |
| Red | 3000 K | Betelgeuse |

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## MEASURING SURFACE TEMPERATURE


(a)

(b)

Figure 16.14 Photon and Neutrino Paths in the Sun. (a) Because photons generated by fusion reactions in the solar interior travel only a short distance before being absorbed or scattered by atoms and sent off in random directions, estimates are that it takes between 100,000 and 1,000,000 years for energy to make its way from the center of the Sun to its surface. (b) In contrast, neutrinos do not interact with matter but traverse straight through the Sun at the speed of light, reaching the surface in only a little more than 2 seconds.

## MEASURING SURFACE TEMPERATURE



Object


## MEASURING SURFACE TEMPERATURE



## MEASURING SURFACE TEMPERATURE



## FIGURE 5.3

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Making Waves. An oscillation in a pool of water creates an expanding disturbance called a wave. (credit: modification of work by "vastateparksstaff"/Flickr)

## ILLUSTRATING THE INVERSE SQUARE LAW



The inverse square law for light: The apparent brightness of a star declines with the square of its distance.

## LUMINOSITY FROM APPARENT BRIGHTNESS AND DISTANCE

Once we have determined a star's luminosity from its apparent brightness and distance, we usually state the result in comparison to the Sun's luminosity.

Studies of the luminosities of many stars have taught us that stars have a wide range of luminosities, with our Sun somewhere in the middle.

$$
\text { apparent brightness }=\frac{\text { luminosity }}{4 \pi \times(\text { distance })^{2}}
$$

## FIGURE 18.15



## THE ELECTROMAGNETIC SPECTRUM

## The Electromagnetic Spectrum



Figure 2 | The electromagnetic spectrum.

## FIGURE 5.9



Action of a Prism. When we pass a beam of white sunlight through a prism, we see a rainbow-colored band of light that we call a continuous spectrum.

## FIGURE 5.12



Continuous Spectrum and Line Spectra from Different Elements. Each type of glowing gas (each element) produces its own unique pattern of lines, so the composition of a gas can be identified by its spectrum. The spectra of sodium, hydrogen, calcium, and mercury gases are shown here.

## THE SPECTRA OF STARS



Figure 17.4 William Huggins (1824-1910) and Margaret Huggins (1848-1915).

## COMPARISON OF EMISSION \& ABSORPTION

Continuous Spectrum

## Emission Lines



Absorption Lines


## HYDROGEN LINES IN HOT AND COLD STARS



## SPECTRAL TYPE

At Harvard College Observatory, Edward Pickering had a large collection of stellar spectra, and hired women (at a lower cost than their male counterparts) from nearby colleges to help classify them. These women were known as the 'Harvard computers'.


Credit: Wikipedia

The spectra were classified according to how strongly the hydrogen lines stood out.



## SPECTRAL TYPE

Williamina Fleming (1857-1911) was the first to categorize stars by their hydrogen spectra, and called the types A, B, C, and so on according to the strength of the hydrogen lines. Was Pickering's maid beforehand, according to some sources.

Williamina's classification system for the hydrogen line strength of stars was from ' A ' class to ' O ' class, with all English letters in between representing a star class

Credit: Wikipedia

## SPECTRAL TYPE



Credit: Wikipedia

Later, Annie Jump Cannon (1863-1941) recognized that by classifying not according to the hydrogen lines, but according to the star's color, or continuum spectrum, and thus in a temperature order, the spectra fell into a natural sequence. She was so fast at this task she would classify several stars a minute and have a scribe record her observations.

She stuck with Fleming's letter designations, but reordered them so that, in temperature order they become:

$$
\mathbf{O}, \mathbf{B}, \mathbf{A}, \mathbf{F}, \mathrm{G}, \mathrm{~K}, \mathrm{M}
$$

Here, O stars are the hottest (bluest) and M stars are the coolest (reddest).

## OBAFGKM (HOW TO REMEMBER)

$$
\begin{aligned}
& \text { O- Oh } \\
& \text { B - Boy } \\
& \text { A - An } \\
& \text { F - F } \\
& \text { G - Grade } \\
& \text { K - Kills } \\
& \text { M - Me }
\end{aligned}
$$

## THE LETTER CLASSIFICATION IS SUBDIVIDED WITH A NUMBER

Notice that the letter classification is subdivided with a number, so the strongest hydrogen lines are in an A0 star, and an A1, A2, etc. are slightly cooler up to A9. Then next cooler star is F0, and so on.

Notice also that the hydrogen lines are quite weak in the hottest stars (O stars).

The Sun is classified as a G2 star -- its hydrogen lines are not very strong.

## FIGURE 17.5



## SPECTRAL TYPE



Adapted from data in the electronic version of "A Library of Stellar Spectra," by Jacoby G.H., Hunter D.A., Christian C.A. Astrophys. J. Suppl. Ser., 56, 257 (1984).

## FIGURE 17.6



Spectra of Stars with Different Spectral Classes. This image compares the spectra of the different spectral classes. The spectral class assigned to each of these stellar spectra is listed at the left of the picture. The strongest four lines seen at spectral type A1 (one in the red, one in the blue-green, and two in the blue) are Balmer lines of hydrogen. Note how these lines weaken at both higher and lower temperatures, as Figure 17.5 also indicates. The strong pair of closely spaced lines in the yellow in the cool stars is due to neutral sodium (one of the neutral metals in Figure 17.5). (Credit: modification of work by NOAO/AURA/NSF)

Spectral Classes for Stars

## TABLE 17.2

| Spectral Class | Color | Approximate Temperature (K) | Principal Features | Examples |
| :---: | :---: | :---: | :---: | :---: |
| O | Blue | > 30,000 | Neutral and ionized helium lines, weak hydrogen lines | 10 Lacertae |
| B | Bluewhite | 10,000-30,000 | Neutral helium lines, strong hydrogen lines | Rigel, Spica |
| A | White | 7500-10,000 | Strongest hydrogen lines, weak ionized calcium lines, weak ionized metal (e.g., iron, magnesium) lines | Sirius, Vega |
| F | Yellowwhite | 6000-7500 | Strong hydrogen lines, strong ionized calcium lines, weak sodium lines, many ionized metal lines | Canopus, Procyon |
| G | Yellow | 5200-6000 | Weaker hydrogen lines, strong ionized calcium lines, strong sodium lines, many lines of ionized and neutral metals | Sun, Capella |
| K | Orange | 3700-5200 | Very weak hydrogen lines, strong ionized calcium lines, strong sodium lines, many lines of neutral metals | Arcturus, <br> Aldebaran |
| M | Red | 2400-3700 | Strong lines of neutral metals and molecular bands of titanium oxide dominate | Betelgeuse, Antares |
| L | Red | 1300-2400 | Metal hydride lines, alkali metal lines (e.g., sodium, potassium, rubidium) | Teide 1 |
| T | Magenta | 700-1300 | Methane lines | Gliese 229B |
| Y | Infrared ${ }^{1}$ | < 700 | Ammonia lines | WISE $1828+2650$ |


Figure 17.8 Brown Dwarfs. This illustration shows the sizes and surface temperatures of brown dwarfs Teide 1, Gliese 229B, and WISE1828 in relation to the Sun, a red dwarf star (Gliese 229A), and Jupiter. (credit: modification of work by MPIA/V. Joergens)

## FIGURE 17.9

Both spectra are from stars of the same apparent temperature. Narrower lines are thought to indicate higher pressure within the star.


## FIGURE 17.10 RADIAL VELOCITY OF STARS

The Doppler Shift


Red-shifted


Stationary


Blue-shifted

| 400 | 500 | 600 | 700 | 800 |
| :---: | :---: | :---: | :---: | :---: |
|  |  | Wavelength (nm) |  |  |
|  |  |  |  |  |

## FIGURE 17.13 PROPER MOTION OF STARS



Proper Motion and Velocity of a Star

## FIGURE 17.14 ROTATION OF STARS

## INTERMISSION

## ASTRONOMY

Chapter 18 THE STARS: A CELESTIAL CENSUS

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## HOW CAN WE OBTAIN MORE INFORMATION ABOUT THE EXPECTED LIFETIME OF A STAR SUCH AS OUR SUN?

## TABLE 18.1 - OUR STELLAR ‘NEIGHBORHOOD’

Stars within 21 Light-Years of the Sun

| Spectral Type | Number of Stars |
| :--- | :--- |
| A | 2 |
| F | 1 |
| G | 7 |
| K | 17 |
| M | 94 |
| White dwarfs | 8 |
| Brown dwarfs | 33 |

Table 18.1

## FIGURE 18.2



Figure 18.2 Dwarf Simulation. This computer simulation shows the stars in our neighborhood as they would be seen from a distance of 30 light-years away. The Sun is in the center. All the brown dwarfs are circled; those found earlier are circled in blue, the ones found recently with the WISE infrared telescope in space (whose scientists put this diagram together) are circled in red. The common M stars, which are red and faint, are made to look brighter than they really would be so that you can see them in the simulation. Note that luminous hot stars like our Sun are very rare. (credit: modification of work by NASA/ JPL-Caltech)

## FIGURE 18.2


(a)

(b)

(c)

Figure 18.3 The Closest Stars. (a) This image, taken with a wide-angle telescope at the European Southern Observatory in Chile, shows the system of three stars that is our nearest neighbor. (b) Two bright stars that are close to each other (Alpha Centauri A and B) blend their light together. (c) Indicated with an arrow (since you'd hardly notice it otherwise) is the much fainter Proxima Centauri star, which is spectral type M. (credit: modification of work by ESO)

## FIGURE 18.4




Revolution of a Binary Star. This figure shows seven observations of the mutual revolution of two stars, one a brown dwarf and one an ultra-cool L dwarf. Each red dot on the orbit, which is shown by the blue ellipse, corresponds to the position of one of the dwarfs relative to the other. The reason that the pair of stars looks different on the different dates is that some images were taken with the Hubble Space Telescope and others were taken from the ground. The arrows point to the actual observations that correspond to the positions of each red dot. From these observations, an international team of astronomers directly measured the mass of an ultra-cool brown dwarf star for the first time. Barely the size of the planet Jupiter, the dwarf star weighs in at just $8.5 \%$ of the mass of our Sun. (credit: modification of work by ESA/NASA and Herve Bouy (Max-Planck-Institut für Extraterrestrische Physik/ESO, Germany))

## FIGURE 18.5

## High-mass

star


## Low-mass

 starCenter of mass

Binary Star System. In a binary star system, both stars orbit their center of mass. The image shows the relative positions of two, different-mass stars from their center of mass, similar to how two masses would have to be located on a seesaw in order to keep it level. The star with the higher mass will be found closer to the center of mass, while the star with the lower mass will be farther from it.

## FIGURE 18.6 - MEASURING MASS OF STARS



Motions of Two Stars Orbiting Each Other and What the Spectrum Shows. We see changes in velocity because when one star is moving toward Earth, the other is moving away; half a cycle later, the situation is reversed. Doppler shifts cause the spectral lines to move back and forth. In diagrams 1 and 3 , lines from both stars can be seen well separated from each other. When the two stars are moving perpendicular to our line of sight (that is, they are not moving either toward or away from us), the two lines are exactly superimposed, and so in diagrams 2 and 4 , we see only a single spectral line. Note that in the diagrams, the orbit of the star pair is tipped slightly with respect to the viewer (or if the viewer were looking at it in the sky, the orbit would be tilted with respect to the viewer's line of sight). If the orbit were exactly in the plane of the page or screen (or the sky), then it would look nearly circular, but we would see no change in radial velocity (no part of the motion would be toward us or away from us.) If the orbit were perpendicular to the plane of the page or screen, then the stars would appear to move back and forth in a straight line, and we would see the largest-possible radial velocity variations.

## FIGURE 18.6 - MEASURING MASS OF STARS

Semi-major orbital axis of a binary star system

## $\longrightarrow D^{3}=\left(M_{1}+M_{2}\right) P^{2}$

1


2


3



Figure 18.7 Radial Velocities in a Spectroscopic Binary System. These curves plot the radial velocities of two stars in a spectroscopic binary system, showing how the stars alternately approach and recede from Earth. Note that positive velocity means the star is moving away from us, and negative velocity means the star is moving toward us. The center of mass of the system itself is also moving away from us, indicated by the positive velocity of 40 kilometers per second. The positions on the curve corresponding to the illustrations in Figure 18.6 are marked with the diagram number (1-4).

Period of one revolution of the binary system

## FIGURE 18.8



(a)

(b)

Figure 18.8 Brown Dwarfs in Orion. These images, taken with the Hubble Space Telescope, show the region surrounding the Trapezium star cluster inside the star-forming region called the Orion Nebula. (a) No brown dwarfs are seen in the visible light image, both because they put out very little light in the visible and because they are hidden within the clouds of dust in this region. (b) This image was taken in infrared light, which can make its way to us through the dust. The faintest objects in this image are brown dwarfs with masses between 13 and 80 times the mass of Jupiter. (credit a: NASA, C.R. O'Dell and S.K. Wong (Rice University); credit b: NASA; K.L. Luhman (Harvard-Smithsonian Center for Astrophysics) and G. Schneider, E. Young, G. Rieke, A. Cotera, H. Chen, M. Rieke, R. Thompson (Steward Observatory))

## FIGURE 18.8



Figure 18.9 Mass-Luminosity Relation. The plotted points show the masses and luminosities of stars. The three points lying below the sequence of points are all white dwarf stars.

## FIGURE 18.12

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Height versus Weight. The plot of the heights and weights of a representative group of human beings. Most points lie along a "main sequence" representing most people, but there are a few exceptions.

## FIGURE 18.13



Hertzsprung (1873-1967) and Russell (1877-1957). (a) Ejnar Hertzsprung and (b) Henry Norris Russell independently discovered the relationship between the luminosity and surface temperature of stars that is summarized in what is now called the $\mathrm{H}-\mathrm{R}$ diagram.

## FIGURE 18.14


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## FIGURE 18.15



Schematic H-R Diagram for Many Stars. Ninety percent of all stars on such a diagram fall along a narrow band called the main sequence. A minority of stars are found in the upper right; they are both cool (and hence red) and bright, and must be giants. Some stars fall in the lower left of the diagram; they are both hot and dim, and must be white dwarfs.

## TABLE 18.3

Characteristics of Main-Sequence Stars

| Spectral Type | Mass (Sun=1) | Luminosity (Sun = 1) | Temperature | Radius (Sun = 1) |
| :--- | :--- | :--- | :--- | :--- |
| O5 | 40 | $7 \times 10^{5}$ | $40,000 \mathrm{~K}$ | 18 |
| B0 | 16 | $2.7 \times 10^{5}$ | $28,000 \mathrm{~K}$ | 7 |
| A0 | 3.3 | 55 | $10,000 \mathrm{~K}$ | 2.5 |
| F0 | 1.7 | 5 | 7500 K | 1.4 |
| G0 | 1.1 | 1.4 | 6000 K | 1.1 |
| K0 | 0.8 | 0.35 | 5000 K | 0.8 |
| M0 | 0.4 | 0.05 | 3500 K | 0.6 |

## TABLE 18.3


(a)

(b)

Figure 18.17 Two Views of Sirius and Its White Dwarf Companion. (a) The (visible light) image, taken with the Hubble Space Telescope, shows bright Sirius A, and, below it and off to its left, faint Sirius B. (b) This image of the Sirius star system was taken with the Chandra X-Ray Telescope. Now, the bright object is the white dwarf companion, Sirius B. Sirius A is the faint object above it; what we are seeing from Sirius is probably not actually X-ray radiation but rather ultraviolet light that has leaked into the detector. Note that the ultraviolet intensities of these two objects are completely reversed from the situation in visible light because Sirius B is hotter and emits more higher-frequency radiation. (credit a: modification of work by NASA, H.E. Bond and E. Nelan (Space Telescope Science Institute), M. Barstow and M. Burleigh (University of Leicester) and J.B. Holberg (University of Arizona); credit b: modification of work by NASA/SAO/CXC)

## FIGURE 18.16



The Sun and a Supergiant. Here you see how small the Sun looks in comparison to one of the largest known stars: VY Canis Majoris, a supergiant.

## FIGURE 18.7



Radial Velocities in a Spectroscopic Binary System. These curves plot the radial velocities of two stars in a spectroscopic binary system, showing how the stars alternately approach and recede from Earth. Note that positive velocity means the star is moving away from us relative to the center of mass of the system, which in this case is 40 kilometers per second. Negative velocity means the star is moving toward us relative to the center of mass. The positions on the curve corresponding to the illustrations in Figure 18.6 are marked with the diagram number (1-4).

## FIGURE 18.10



Time

Light Curve of an Eclipsing Binary. The light curve of an eclipsing binary star system shows how the combined light from both stars changes due to eclipses over the time span of an orbit. This light curve shows the behavior of a hypothetical eclipsing binary star with total eclipses (one star passes directly in front of and behind the other). The numbers indicate parts of the light curve corresponding to various positions of the smaller star in its orbit. In this diagram, we have assumed that the smaller star is also the hotter one so that it emits more flux (energy per second per square meter) than the larger one. When the smaller, hotter star goes behind the larger one, its light is completely blocked, and so there is a strong dip in the light curve. When the smaller star goes in front of the bigger one, a small amount of light from the bigger star is blocked, so there is a smaller dip in the light curve.

## FIGURE 18.11



Time

Light Curve of an Edge-On Eclipsing Binary. Here we see the light curve of a hypothetical eclipsing binary star whose orbit we view exactly edge-on, in which the two stars fully eclipse each other. From the time intervals between contacts, it is possible to estimate the diameters of the two stars.

# READ CHAPTER 17 

READ CHAPTER 18
Homework Problems on Canvas
Due by Sunday night
No Late Submissions


[^0]:    Table 17.1

