Lab 6

The Hertzsprung-Russell Diagram and Stellar Evolution

6.1 Overview

Exercise six focuses on stellar properties and evolution for individual stars and for stellar clusters. It begins with observables such as stellar brightness and color, and uses the Hertzsprung-Russell (H-R) Diagram as a vehicle to track how stellar properties change with age. We begin with an introduction to stellar properties of Main Sequence and giant stars that uses a Nebraska Astronomy Applet Project (NAAP) web-application to illustrate connections between stellar luminosity, temperature, and radius.

The Pleiades cluster represents a young stellar cluster, one with minimal evolution away from the Main Sequence. We work from an optical H-R diagram for the cluster to reinforce ideas about the Main Sequence and to practice manipulating stellar magnitudes. The logarithmic magnitude scale poses a significant challenge for many students, so this exercise contains numerous examples (as does the video tutorial) illustrating how to properly compare apparent and absolute magnitudes.

Our M67 activity (see Figure 6.1) gives students a chance to construct their own H-R Diagram by fitting apertures to individual stars of various colors and brightnesses on a multi-band color Sloan Digital Sky Survey (SDSS) image of the cluster. Robert Lupton was kind enough to provide us with the image, one which would make Antoni Gaudi proud due to its distinctive color palette and strong blue-red contrasts. The cluster image is presented through a specialized web-application, allowing students to focus on how to properly fit apertures that contain the entire stellar light profile but a minimum of neighboring objects and background light. In addition to the cluster image, students evaluate a radial light profile within and around each aperture as it is fit, and the sampled stars are placed on an H-R diagram at
positions derived from the student-determined luminosities and colors. After fitting a sample of twelve stars for themselves, they then select a model corresponding to a particular cluster age by fitting the cluster turn-off point on the H-R Diagram to data for the entire cluster.

Figure 6.1: A screen capture of our M67 H-R diagram and stellar aperture fitting web-application. The radial profile in the upper left-hand corner shows the distribution of light within the aperture currently being fit on the M67 cluster image. (The star is marked with a green aperture on the image.) Students can vary the aperture size and position with the right-hand side control panel, using aperture controls that match those used in exercise four to fit craters on the Martian surface. The H-R diagram in the lower left-hand corner shows the distribution of stellar luminosities and colors for stars covering a range of properties, selected and fit by students. The four colored tracks illustrate the patterns formed by stars evolving off of the Main Sequence within cluster of various ages. After students fit a sample of twelve stars, the rest of the cluster is added to the H-R Diagram to give students a large sample when selecting an age track for M67.

6.2 Learning Objectives

After completing this laboratory exercise, the student should be able to do the following:

- Understand the difference between apparent properties, which vary with distance, and intrinsic properties. In particular, distinguish between (a) apparent and absolute magnitude, and (b) apparent magnitude and intrinsic luminosity.

- Describe the magnitude scale and explain how magnitudes are determined. In particular, (a) relate magnitude to brightness, (b) comprehend why fainter objects have larger
magnitudes, (c) recognize that the magnitude scale is not linear, and (d) understand that brightness can be measured by counts registered in pixels of images, which can be converted mathematically to magnitudes.

- Realize that a star’s color can be measured by subtracting magnitudes defined by fluxes from two different filters.

- Visualize the effects of varying the position and size of an aperture placed on an image, and relate them to good and bad technique in measuring stellar fluxes.

- Become comfortable with the H-R Diagram, and identify different forms it can take. In particular, (a) connect the x-axis to temperature, color, and spectral type, and connect the y-axis to luminosity and absolute magnitude, or to apparent magnitude for members of clusters, (b) visualize lines of constant radius, and (c) identify the Main Sequence and the position of the Sun, and the regions where giants and dwarfs of varied colors are found.

- Realize that astronomers can construct H-R diagrams using certain observed quantities (apparent magnitude, color, spectral class, and parallax measurements or other distance estimators) to then study the physical properties of a star such as intrinsic luminosity, temperature, mass, and radius.

- Comprehend that how quickly a star evolves depends fundamentally on its initial mass.

- Explain how the H-R diagram is used by astronomers to study the evolution of stars.

- Use the Stefan-Boltzmann Law to shift between luminosity, temperature, and radius (deriving any one from the other two), connect this relationship to the H-R diagram, and understand the scaling in solar units of stellar properties along the H-R diagram.

- List the fundamental properties a star is born with that determine its other properties, and connect these with the behavior of homogeneous populations in star clusters.

- Appreciate that the appearance of a stellar cluster H-R diagram changes with the age of the cluster in a predictable way, and that this can be used to estimate cluster ages.

6.3 **Keywords**

Aperture – A circle, or ellipse, with an open center. Astronomers often place an aperture around a single star or galaxy, and then add up all the light contained within this region in order to determine how bright the object is.

Arcsecond – An arcsecond is a unit of angular size, equal to 1/60 of an arcminute or 1/3600
of a degree (recall that there are 90 degrees in a right angle). Astronomers often measure
the angular separation between neighboring objects on the sky in units of arcseconds.

Astronomical unit – The average distance between the Earth and the Sun, equal to $1.5 \times 10^8$
kilometers.

Blue supergiants – Rare hot, blue stars with very high mass and luminosity that are ten
to fifty times the Sun’s size. In the H-R diagram, they occupy a region above the Main
Sequence and on the left.

Color index – A number used to gauge a star’s color, or relative intensity, at two wavelengths.
Often based on the difference between how bright a star appears in two different filters, e.g.
$B-V$ for the blue and visual filters.

Hertzsprung-Russell Diagram (H-R Diagram) – A plot of intrinsic brightness (luminosity or
absolute magnitude) versus color index (or the analogous surface temperature or spectral
class) for stars, used to study stellar evolution for stars of various types and for clusters of
stars.

Light year – A unit of distance (not time), equal to the distance which light travels in a year.
One light year is equal to 0.307 parsecs.

Luminosity – A measure of intrinsic brightness defined by how much energy a star (or other
object) radiates into space per second.

Main Sequence – A narrow region running across the H-R diagram, where hydrogen-burning
stars are found. As stars grow old and run out of fuel, they evolve away from the Main
Sequence.

Magnitude, absolute – The brightness of an object on the logarithmic magnitude scale, as
observed from a distance of ten parsecs. This provides a measure of intrinsic brightness.

Magnitude, apparent – The brightness of an object based on the logarithmic magnitude
scale, as observed from Earth. Two equivalent stars (with the same absolute magnitude)
will have different apparent magnitudes if one lies closer to Earth than the other does.

Magnitude scale – A logarithmic scale for gauging the brightness of astronomical objects.
It is based on historical measurements done by eye in which first magnitude stars were the
brightest and sixth the faintest, so brighter objects have smaller magnitude values.

Parsec – A unit of distance defined as the distance at which an object exhibits a parallax
shift of one arcsecond. As the Earth rotates around the Sun and shifts by a length of one
astronomical unit, a star which lies one parsec away from Earth will appear to shift by one
arcsecond across the sky. One parsec is equal to 3.26 light years or 206,265 astronomical
units.

Red dwarfs – Cool, red, low luminosity stars with less mass and smaller sizes than the Sun.
In the H-R diagram, they are Main Sequence objects, located to the lower right of the Sun’s position. Because red dwarfs are such low-mass stars, they spend much more time on the Main Sequence than solar-mass or more massive counterparts.

Red giants – Cool, red, high-luminosity stars that are hundreds of times the Sun’s size. In the H-R diagram, they occupy a region well off the Main Sequence to the upper right. The progenitors of red giants are Main Sequence stars, which burn through their hydrogen reserves and then move into the giant phase.

Spectral class – A classification based on the appearance of a stellar spectrum, analogous to the temperature sequence, with blue O class stars being hottest, yellow G stars like the Sun being intermediate, and red M stars being cooler.

Star – A hot, glowing, spherical mass of gas, dominated by hydrogen. Stars are typically found in stable configurations in which the inward-directed force of gravity is balanced by the outward radiation pressure due to nuclear fusion reactions in the cores.

Star cluster – A group of hundreds or thousands of stars bound together by gravity, which formed at a single epoch from a giant cloud of interstellar gas and dust.

Stellar evolution – The process by which a star changes in size, luminosity, temperature, and appearance, as it ages and consumes its fuel. The speed of these changes is driven primarily by stellar mass. The most massive stars may shine for only a few million years, while the least massive could last hundreds of billions of years.

Stefan-Boltzmann Law – A mathematical relationship describing the behavior of spherical, idealized radiators (a.k.a. stars), connecting luminosity $L$, temperature $T$, and radius $R$: $L = (4\pi\sigma)T^4R^2$, where $\sigma$ is the Stefan-Boltzmann constant.

Turn-off point – The point on the H-R diagram for a particular star cluster where its stars are evolving off of the Main Sequence and becoming red giants. The location, usually specified by the corresponding color index, depends on the cluster’s age.

White dwarfs – Hot, low-luminosity stars that are much smaller than the Sun (they are Earth sized!) These old, dying stars are gradually cooling, and growing fainter with time. They are the end-states for intermediate- and low-mass Main Sequence stars which have passed through the giant phase.

6.4 Relevant Lecture Chapters

This laboratory exercises draws heavily upon the material in Chapter 20: The Hertzsprung-Russell Diagram. There are related materials in Chapter 17: Stellar Temperatures, Chapter 18: Nuclear Reactions, and Chapter 21: White Dwarfs.
6.5 References and Notes

1. The H-R exploratory web application is used courtesy of Kevin Lee of the University of Nebraska, Lincoln, and the Nebraska Astronomy Applet Project (NAAP). Questions 2 and 3 in the final (post-lab) questions section were adapted from NAAP materials.

2. The H-R Diagram for the Pleiades presented in Figure 6.4 was created from data for 47 stars taken from the following references. The 14 brightest stars come from Johnson, H. L., Iriarte, B., Mitchell, R. I. & Wisniewski, W. Z., “UBVRIJKL photometry of the bright stars,” 1966, Communications of the Lunar and Planetary Laboratory, 4, 99, and the rest come from Mendoza, E. E., “Multicolor Photometry of Stellar Aggregates,” 1967, Boletin de los Observatorios Tonantzintla y Tacubaya, 4, 149.


4. The M67 H-R Diagram web application sky image is a ugr mosaic created from Sloan Digital Sky Survey (SDSS) data, and is shown courtesy of Robert Lupton and the SDSS. Note that in order to preserve a wide range of visual colors across the image, the cores of the brightest stellar profiles are occasionally flat-topped or contain a small dimple. An appropriate journal reference for the latest SDSS data release is “The Eighth Data Release of the Sloan Digital Sky Survey: First Data from SDSS-III,” by Aihara et al. in The Astrophysical Journal Supplement. vol. 193(2), pp. 29-46 (2011).

5. The H-R diagram for M44 in Figure 6.5 is based on photometric data taken from Johnson, H. L., “Praesepe: Magnitudes and Colors,” 1952, Astrophysical Journal, 116, 640.


7. Figure 6.1 and Figure 6.3 are shown courtesy of Nicole Vogt.