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.

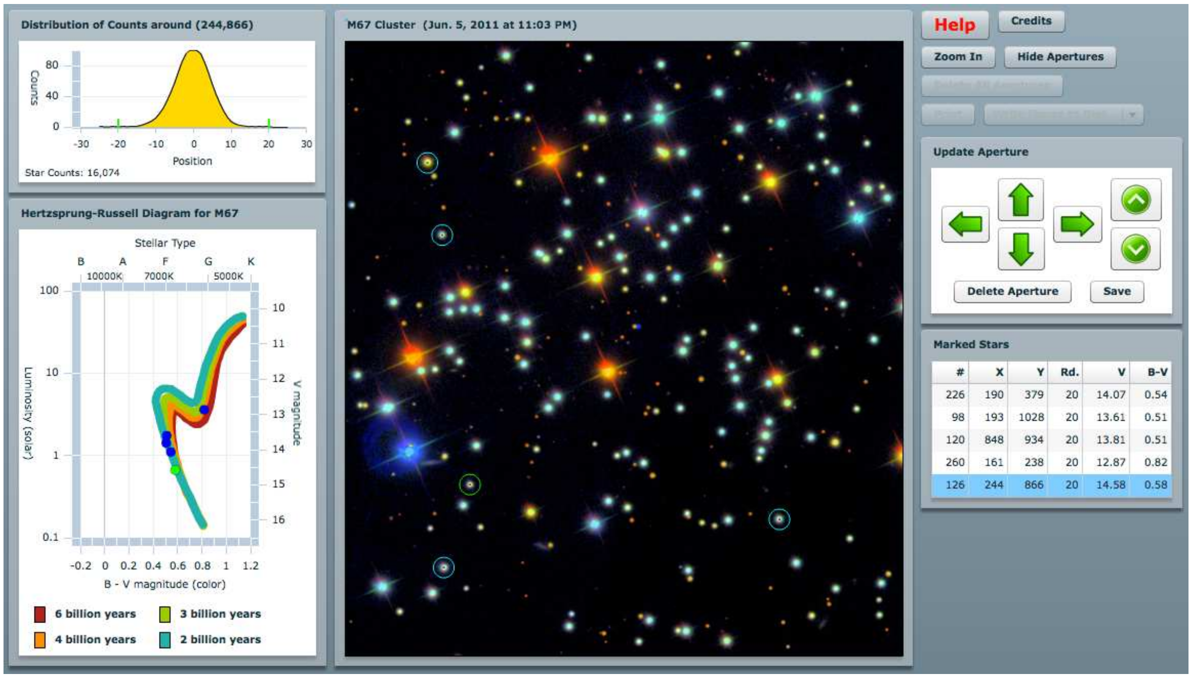

Figure 6.1: A screen capture of our M67 H-R diagram and stellar aperture fitting web-application. The radial profile in the upper left-hand corner shows the distribution of light within the aperture currently being fit on the M67 cluster image. (The star is marked with a green aperture on the image.) 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 type, 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 Teaching Toffees

Teaching toffees are practical tips based on the hard-won experience of fellow instructors.

For all GEAS lab exercises:

Please have students access the list of components for the lab exercise (lab chapter, video tutorial, web applications, report template) directly from the GEAS website so that they use the current version of all tools.

By having them save and share the lab report template, they will have their work backed up automatically and instructors will be able to observe their progress 24/7. This allows instructors to check for appropriate progress towards intermediate goals over a two-week period, and for students and instructors to interact asynchronously through threaded comments placed in the report margins at exactly the point where a question occurs. Note that the Lab #1 video tutorial describes how to work with Google resources, and there is a two-page handout on the lab website as well.

Students sometimes try to complete the lab exercise by skipping over the lab chapter entirely and working from just the report template. This is not an effective learning strategy, nor does it save time. The report template contains only abbreviated forms of the questions with spaces for answers, but none of the context or framework for the questions.

We strongly encourage you to strongly encourage all of your students to watch the video tutorial before beginning to work on the exercise. If a picture is worth a thousand words then a video might be worth a million words. Each tutorial is designed to introduce the scientific concepts that motivate the companion exercise. Because students may be working remotely on their own, it also focuses on the most potentially challenging aspects of each project and walks them through key steps by showing them what they look like in practice.

6.4 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 1.5×10^8 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 type) for stars, used to study stellar evolution for stars of various types and for clusters of stars.

Intrinsic – Inherent, or natural. Astronomers distinguish between the intrinsic brightness of a star, or how much energy it radiates, and the apparent brightness, or how bright it appears when observed from Earth. Intrinsic properties of stars are absolute, while apparent properties change depending on how far away the stars are from us.

Kelvin (K) – A temperature unit, similar to degree Fahrenheit (commonly used in the United States) or Celsius. Astronomers use the Kelvin scale to describe how hot or cool stars are. Stars cooler than 4000 kelvin appear reddish, and those hotter than 7500 kelvin appear bluish. The Sun lies in between these extremes, with a temperature of 5800 kelvin.

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.

Radial – Extending outward from a common center. When a child draws the Sun as a little dot with arrows going out in all directions to show the sunlight escaping, they are drawing radial lines. To plot the radial distribution of light within an aperture centered on an image of a star, imagine placing a series of thin rings around the star. Average the brightness of the light contained within the left half and the right half of each ring, and plot these values from left to right according to how far each ring lies from the center of the star.

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 type – A classification based on the appearance of a stellar spectrum, analogous to the temperature sequence, with blue O type 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.

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 σ is the Stefan-Boltzmann constant.

Stellar – Relating to a star or to stars.

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.

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.

6.5 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.

6.6 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.

3. The M67 H-R Diagram web application utilizes photometric magnitude data taken from Laugalys, V., Kazlauskas, A., Boyle, R. P., Vrba, F. J., Philip, A. G. D., & Straižys, V., "CCD Photometry of the M 67 Cluster in the Vilnius System. II. New Photometry of High Accuracy," 2004, Baltic Astronomy, 13, 1.

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.

6. The reference to the Sun being born in a star cluster is based on Zwart, S. F. P., "The Long Lost Siblings of the Sun," November 2009, Scientific American.

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