Lab 6

The Hertzsprung-Russell Diagram and Stellar Evolution

6.1 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.

6.2 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

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 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 σ is the Stephan-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 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 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 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.

5) 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.