Lab 7. The Age of a Star Cluster

1 Introduction

Perhaps the field of astrophysics that is best understood is stellar structure and stellar evolution. By integrating a few relatively simple equations that relate, mass, pressure, temperature, and energy flow, astronomers can determine both the structure of a star's interior and how the structure will change with time. We will not be concerned with the mathematical techniques used to perform this calculation. Instead, in this lab we will use the results of a stellar evolution calculation to estimate the ages of the oldest stars in the Galaxy. First, as usual, we will review a bit about stellar evolution.

2 How Stars Evolve

Throughout its life, a star is fighting a losing battle against gravity. This is understandable — after all, a star like the Sun contains 2×10^{33} grams of mass, and the self gravitation of such a mass cannot be negated. (There is no "anti-gravity.") In the absence of other forces, the matter of a star would just fall in on itself to a single point. Fortunately, there are forces in the universe that can, at least temporarily, halt the final collapse.

Gas pressure is one such force. Stars are essentially huge balls of gas, and the same force that holds up a bicycle tire holds up stars. However, gas pressure is only effective as long as the temperature of the gas is high. Pressure and temperature are commonly related by an *equation of state,* similar to

$$P = \frac{\rho}{\mu} kT$$

Here, P is the pressure, T the temperature, ρ, the density, and μ the atomic weight. As you can see, temperature and pressure are directly proportional, so any decrease in temperature will result in a decrease in pressure. In the center of a star, the temperatures and pressures are high, but unless some energy source constantly replenishes the heat that leaks out to the star's exterior, the star cannot be stable: in a few million years, the star would collapse.

The energy source that maintains the pressure in the center of a star is nuclear energy from fusion. A star's composition (by mass) is approximately 75% hydrogen, 23% helium, and 2% metals (to an astronomer, anything that is not hydrogen or helium is a metal), and in the center of a normal star, energy is produced by fusing hydrogen to helium. Through a series of nuclear reactions, the most common of which is the proton-proton chain, four hydrogen atoms (protons) are converted into one helium atom (2 protons and 2 neutrons). However, although the number of baryonic particles (protons and neutrons) is conserved in this process, the mass of the particles is not. Four hydrogen atoms weigh more than 1 helium atom, by about 0.71%. This *mass defect* is converted to energy ($E = mc^2$), and it is this energy which gives a star life.

For millions, or billions of years, a star will stay in *hydrostatic equilibrium,* stably burning hydrogen to helium in its core. Over this time, the structure of the star will not change much: as the available fuel (hydrogen) in its core gradually decreases, the star's luminosity may increase by a few tenth's of a magnitude, or its surface temperature may decrease slightly, but not until all the fuel in the center is exhausted will there be any real change in the star's structure.

The rate of energy production inside a star depends on its mass: the higher the mass of the star, the higher the central pressure and temperature, and the higher the rate of nuclear reactions. In fact, the rate of nuclear reactions goes as the fourth or fifth power of temperature, and this is reflected in the main sequence: mass estimates from binary stars show us that stars on the main sequence obey a mass-luminosity relation, with $L \propto M^4$. The high dependence of reaction rate with temperature (or luminosity with stellar mass) means two things: first that high mass stars are *much* more luminous than low mass stars, and second, that high mass stars burn up their fuel *much* faster than low mass stars. We can exploit this fact to learn something about the age of our Galaxy.

Consider a cluster of stars, all at the same distance. We will make two assumptions concerning it. The first is that all the stars in the cluster were born at the same time. Since star formation typically takes place over several thousand years, this is a good assumption for all but the youngest of clusters. The second assumption is that when a star cluster is formed, it is formed with stars of all masses. This, too, is a good assumption. Although the *initial mass function,* which describes the ratio of high-mass to low-mass stars is a matter of much debate in astronomy, virtually all clusters are born with at least some high mass stars.

At the time when a star cluster is formed, all the stars in it are on the zero age main sequence (ZAMS), changing hydrogen to helium in their core. Hence, if you were to make an HR diagram of a cluster during this phase, you would see the entire main sequence populated with stars. However, this would not be the case a million years later. In that time, the most massive, most luminous stars will have used up all the fuel in their core and evolved off the main-sequence. Tthe main-sequence you would see would therefore appear truncated and contain no O-stars. Similarly, the main-sequence of a cluster which is 1 billion years old would contain no O-stars or B-stars. Thus, by measuring the main sequence *turn-off,* astronomers can estimate the age of a cluster.

3 The Lab

For this lab, you have at your disposal theoretical calculations of what an HR diagram of a cluster would look like as a function of time. These lines, which trace out the locus of stars of a single age, are called *isochrones.* The ones here were created in 1986 by astrophysicists at Yale University, and are color-magnitude diagrams of star clusters as a function of time. You will use the isochrones to determine the age of the star cluster that you measured in the previous lab.

3.1 Procedure

To read the isochrone data, you will need the program, **isoread.pro**. Copy it to your directory in the usual manner, *i.e.,*

cp /afs/psu.edu/users/m/a/mab22/lab7/isoread.pro isoread.pro

The isochrone files themselves are listed at the end of this lab. You may want to **page** through them to see what they contain. (You may also want to look at **isoread.pro** to see what it does.) Now enter IDL.

1. First, plot your color-magnitude diagram of 47 Tuc that you measured in Lab 6. (Remember, to adjust the **!psym**, **xrange**, and **yrange** to make the plot presentable.

2. Read in an isochrone with the program **isoread** by typing

   isoread, *filename, vmag, bvcolor*

   where *filename* is the name of the file ENCLOSED IN QUOTES, and *vmag* and *bvcolor* are arrays that contain the absolute V magnitude (M_V) and $B-V$ color. For comparison with 47 Tuc, change these absolute magnitudes to apparent magnitudes, using the distance modulus you computed in the previous lab.

3. Now set **!psym = 0** and plot your isochrone on top of your color-magnitude diagram, using

   oplot, *bvcolor, vmag*

   This command acts the same as **plot**, except that it keeps the same scale as the previous plot and does not erase the screen.

4. Repeat steps 2 and 3 for the other isochrones. You do not have to plot each curve, but you should plot enough so that you can estimate the age of the cluster. What is the age of the cluster, and what would you estimate the error is on this number? What effect would interstellar extinction have on your result?

Table 1: Isochrone Data

Filename	Age ($\times 10^9$ years)
/afs/psu.edu/users/m/a/mab22/lab7/iso_150myr.dat	0.15
/afs/psu.edu/users/m/a/mab22/lab7/iso_200myr.dat	0.20
/afs/psu.edu/users/m/a/mab22/lab7/iso_350myr.dat	0.35
/afs/psu.edu/users/m/a/mab22/lab7/iso_500myr.dat	0.50
/afs/psu.edu/users/m/a/mab22/lab7/iso_750myr.dat	0.75
/afs/psu.edu/users/m/a/mab22/lab7/iso_1gyr.dat	1.00
/afs/psu.edu/users/m/a/mab22/lab7/iso_2gyr.dat	2.00
/afs/psu.edu/users/m/a/mab22/lab7/iso_3gyr.dat	3.00
/afs/psu.edu/users/m/a/mab22/lab7/iso_4gyr.dat	4.00
/afs/psu.edu/users/m/a/mab22/lab7/iso_5gyr.dat	5.00
/afs/psu.edu/users/m/a/mab22/lab7/iso_6gyr.dat	6.00
/afs/psu.edu/users/m/a/mab22/lab7/iso_7gyr.dat	7.00
/afs/psu.edu/users/m/a/mab22/lab7/iso_8gyr.dat	8.00
/afs/psu.edu/users/m/a/mab22/lab7/iso_9gyr.dat	9.00
/afs/psu.edu/users/m/a/mab22/lab7/iso_10gyr.dat	10.00
/afs/psu.edu/users/m/a/mab22/lab7/iso_11gyr.dat	11.00
/afs/psu.edu/users/m/a/mab22/lab7/iso_12gyr.dat	12.00
/afs/psu.edu/users/m/a/mab22/lab7/iso_13gyr.dat	13.00
/afs/psu.edu/users/m/a/mab22/lab7/iso_14gyr.dat	14.00
/afs/psu.edu/users/m/a/mab22/lab7/iso_15gyr.dat	15.00
/afs/psu.edu/users/m/a/mab22/lab7/iso_16gyr.dat	16.00
/afs/psu.edu/users/m/a/mab22/lab7/iso_17gyr.dat	17.00
/afs/psu.edu/users/m/a/mab22/lab7/iso_18gyr.dat	18.00
/afs/psu.edu/users/m/a/mab22/lab7/iso_20gyr.dat	20.00