SEQUENCING THE STARS

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Using images acquired with modern CCD cameras, amateur astronomers can make Hertzsprung-Russell diagrams from their own images of clusters. In this way, we can demonstrate for ourselves that globular clusters are old and far whereas open clusters tend to be young and near.

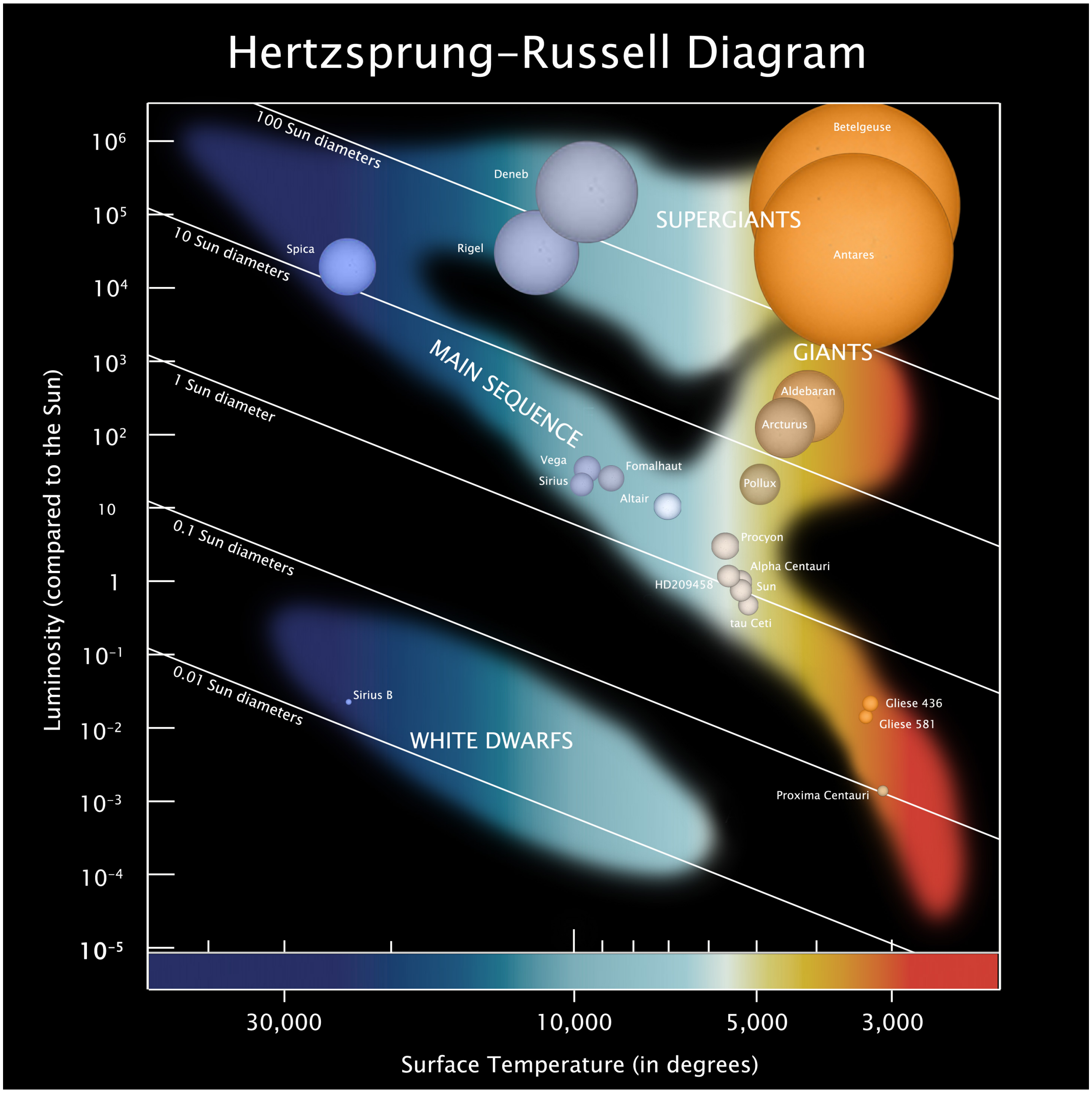
It is easy to forget that less than 100 years ago, no one knew the process by which stars produce light. Today, we understand quite well that stars, which are composed mostly of hydrogen, produce energy by nuclear fusion. The enormous pressure created by the mass of a star causes pairs of hydrogen nuclei in its core to fuse into a helium nucleus thereby converting a small amount of mass into energy. Hence, we have starlight.

For most of its lifetime, a star's brightness and color depend almost exclusively on a single variable—how much hydrogen was present at its birth, when a cloud of hydrogen coalesced under the influence of gravity to form the star. In other words, brightness and color depend on mass. Stars significantly more massive than our Sun are hot, bright, and blue—the more massive, the hotter, brighter, and bluer. Stars less massive than our Sun are fainter, cooler, and redder. Hence, if we make a scatter plot of color versus absolute brightness (luminosity) most points in this scatter plot fall roughly on a line, called the *Main Sequence*. Such plots were first constructed by Ejnar Hertzsprung and Henry Norris Russell in 1910 (one hundred years ago) and are therefore called *Hertzsprung-Russell diagrams*, or HR-diagrams for short.

The most difficult part in constructing an HR-diagram is to find the actual luminosity of each star. For this, we need to know how far away the star is. If we know that, we can convert its apparent magnitude (the magnitude it appears to us in the night sky) to its absolute magnitude (the magnitude it would appear to an observer at a standard distance from the star, say, 10 parsecs). Absolute magnitude is essentially equivalent to luminosity. It tells us how bright a star actually is. But, knowing the distance is key. Without knowing distance, it is difficult to relate apparent magnitude to absolute magnitude. For this reason, it was really quite an achievement when Hertzsprung and Russell first constructed their diagrams. However, clusters (both open and globular) give us a way to circumvent the distance issue. The stars in a cluster are all at about the same distance from us. Hence, for such stars, we can use apparent brightness as a surrogate for luminosity.

To illustrate, I recently took a sequence of short-exposure pictures of the Beehive Cluster (M44). This cluster is large, listed in catalogues as 95 × 95 arcminutes, and so I opted to do a two-frame mosaic. My mosaic doesn't cover the entire cluster but I captured a big central part of it. I actually made three separate mosaics, using short exposures (0.08 seconds), medium exposures (8 seconds), and long exposures (80 seconds). Then, I used the freeware program SOURCE EXTRACTOR, commonly referred to as SExtractor, to identify all the stars in these images and for each one an estimate of its color and brightness. SExtractor produces a plain text file listing data for each star, one star per line. I culled from the lists any star whose flux was such that the brightest pixels would have saturated the CCD chip. Then I normalized the fluxes to represent what I would have gotten from a 1 second exposure and I combined the three lists into one master list. I imported this master list into a plotting program (MATLAB) and made a plot of color versus luminosity. That plot is shown here. The main sequence is plainly evident! As with any wide-field image, there are several stars that do not belong to the object under study. In this case, these are fainter background stars whose colors are largely uncorrelated with apparent brightness because they are at varying distances and therefore apparent brightness tells us nothing about absolute brightness.

The main sequence is only part of the story. When a star gets old, generally after billions of years, it exhausts the hydrogen available for fusion in its core. At this point, which marks the beginning of a prolonged death process (lasting

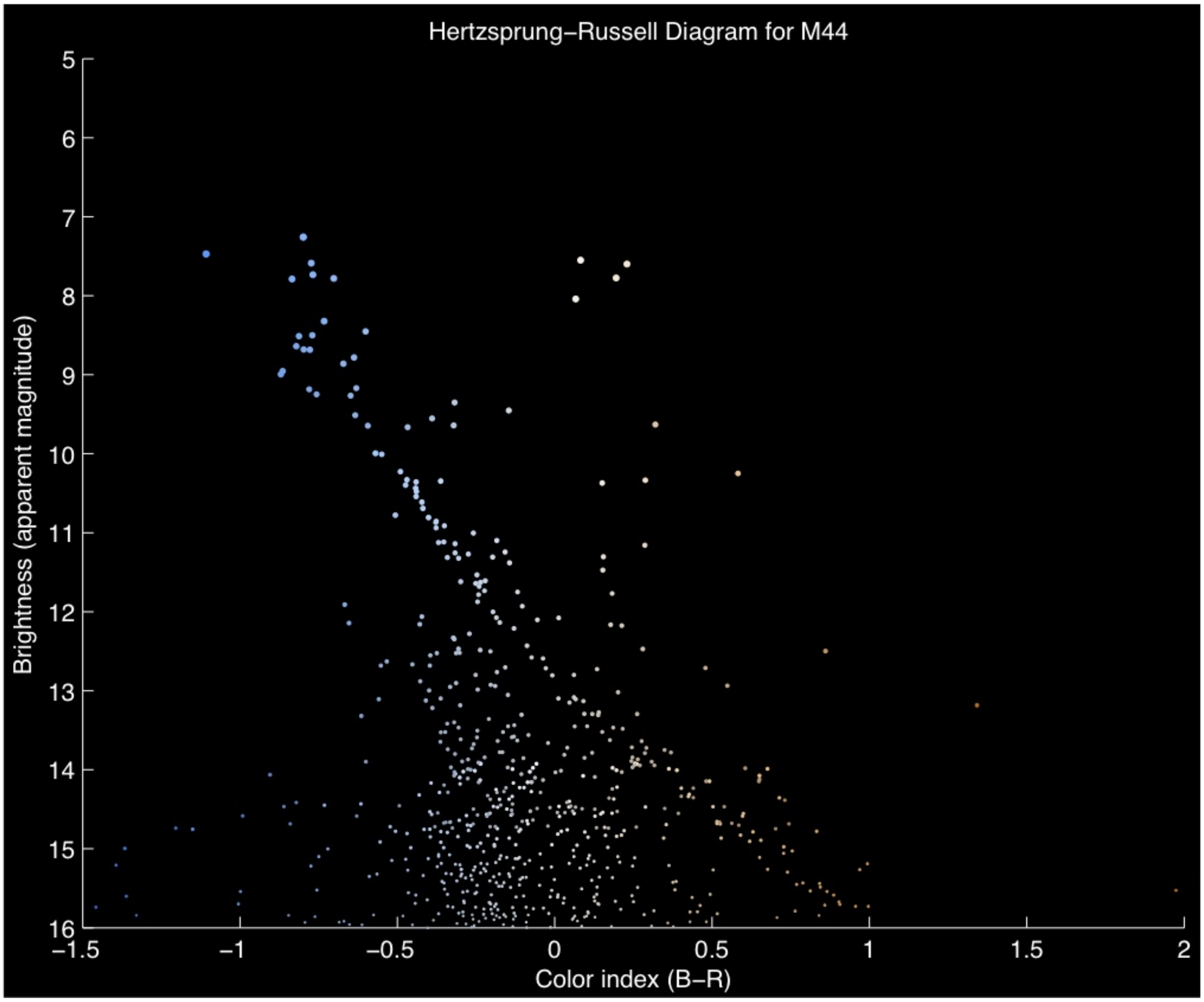


about a million years or so), other fusion reactions take over. No longer is there a simple relationship between mass, color, and luminosity. In the first stage of this death dance, the star grows in size, cools, and becomes redder. Such old stars form a distinct branch in an HR-diagram called the *red giant branch*. Stars that started out with plenty of mass, burn rapidly and die young (after merely hundreds of millions of years) whereas stars that started out with less mass spend billions of years as main sequence stars before eventually becoming red giants. Of course, the final stage of stellar death also depends on the mass of the star—massive stars eventually explode and are seen for a short time as supernovae whereas less massive stars expire more gracefully by sloughing off their outer shell, which we see as planetary nebulae, eventually leaving behind just a faint remnant of a star called a *white dwarf*.

White-dwarfs are far from red-giants on the HR diagram. How does the evolution from one to the other look on such a diagram? As a red giant ages, it eventually begins to fuse helium into carbon. At this point, the star turns bluer, moving to the left on the HR diagram. These stars form a

Open Cluster M44 (Beehive). Image taken by the author.

second prominent branch called the *horizontal branch*. After that, at the last stage, the star rapidly diminishes in brightness and becomes a very faint white dwarf. This last transition takes place over a relatively short time interval and therefore we see very few stars making this transition.



The Main Sequence is clearly visible.

Globular clusters are known to be very old—roughly as old as our galaxy itself. In fact, all of the stars in a globular cluster formed at about the same time billions of years ago. There are no remaining bright, hot, blue stars in globular clusters. They have all lived, loved, and died billions of years ago. All that remains are the less massive, cooler, stars. There are hundreds of thousands of them in a globular cluster. The brightest stars one sees in these clusters have left the main sequence and are in the late red-giant phase of their evolution. Hence, the bright stars in an HR-diagram of a globular cluster are red giants. The brighter the star, the redder and "gianter" it is. Take a look at the illustration showing the HR-diagram for M13 constructed from the professional catalogs in the publicly accessible VizieR database (http://vizier.u-strasbg.fr/viz-bin/VizieR). This plot is typical for a globular cluster. The brightest stars are red-orange. The red-giant branch forms a narrow curve that arcs up and to the right. We also see a branch consisting of medium brightness blue stars. These stars are on a branch called the *horizontal branch* (even though it looks more vertical than horizontal in this particular case). Stars on the horizontal branch are more massive than red giants and are therefore further along in their stellar life cycle. Normally, the horizontal branch connects horizontally over to the red giant branch. The whitish stars on this horizontal branch are the famous *RR-Lyrae* stars. These are *variable stars* meaning that their magnitude varies with time (over the course of hours). Hence, they don't have one particular magnitude to plot on the vertical axis and I believe for this reason may have been purged in the VizieR database from which the chart shown here was made.

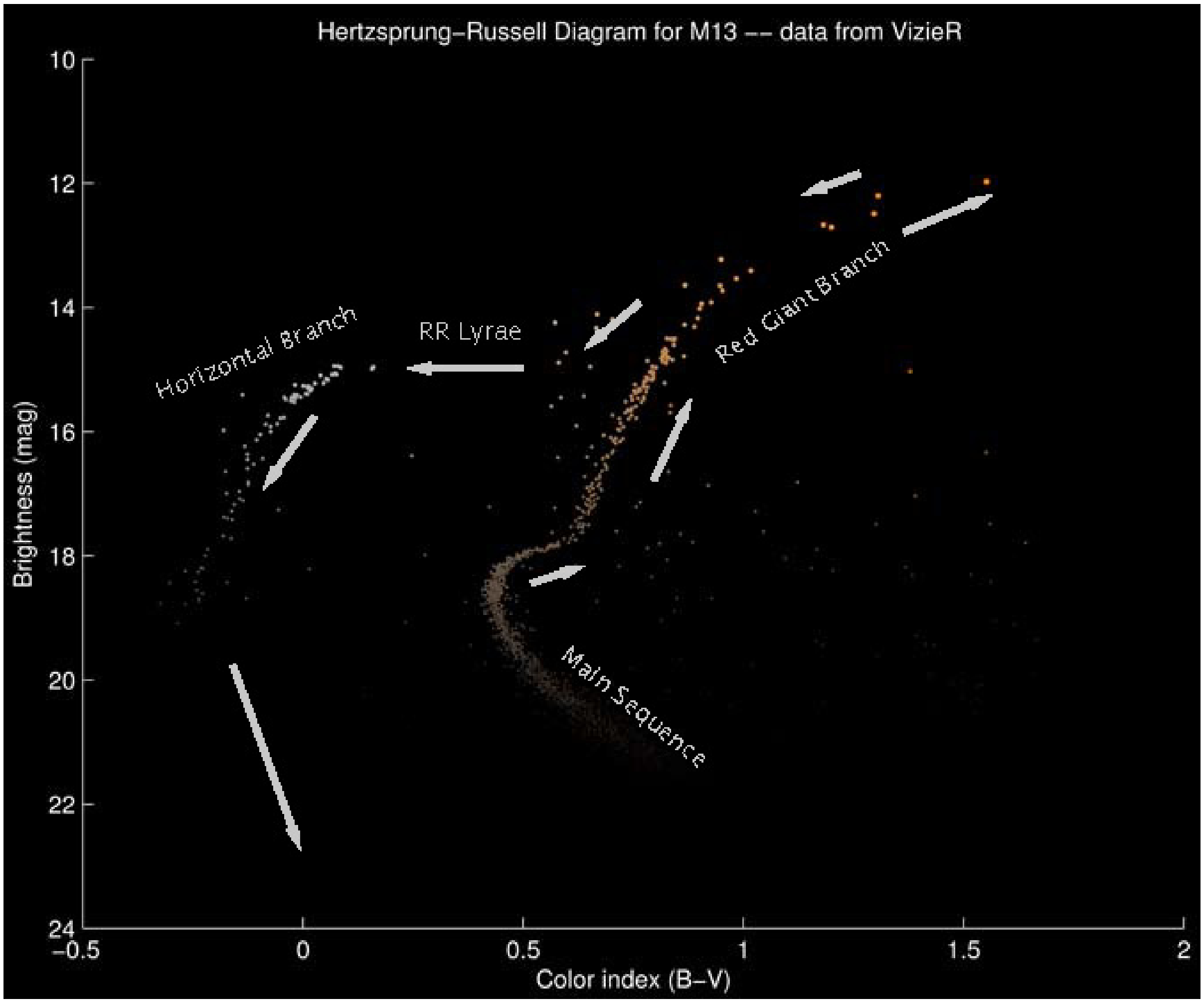
Globular Cluster M13. Image taken by the author.

I have taken photographs of many globular clusters over the past several years. Recently, I constructed HR diagrams for them. A few are shown here.

The first thing to notice is that my HR diagram for M13 looks similar to the one shown before. There are, of course, some differences. I'm showing more stars. The VizieR database that I used for the "professional" HR diagram excludes stars that are crowded by nearby stars making it hard to obtain accurate color and luminosity information. My program is not so cautious. Also, the VizieR diagram uses the accepted method of computing star color, which is to subtract the so-called visual magnitude (V) from the blue magnitude (B). This is called the *B-V color-index*. There is a standard specification for the B and V filters that one is to use. My pictures were taken with the filters I have, namely red (R), green (G), and blue (B) filters. It seemed reasonable to use B-R magnitudes in place of B-V. Hence, for each star, I assigned a slightly different numerical value for its color than in the VizieR plot.

My plots show some stars of various colors that seem to be too bright. These are nearby stars that don't belong to the globular cluster but just happen to be in the field of view.

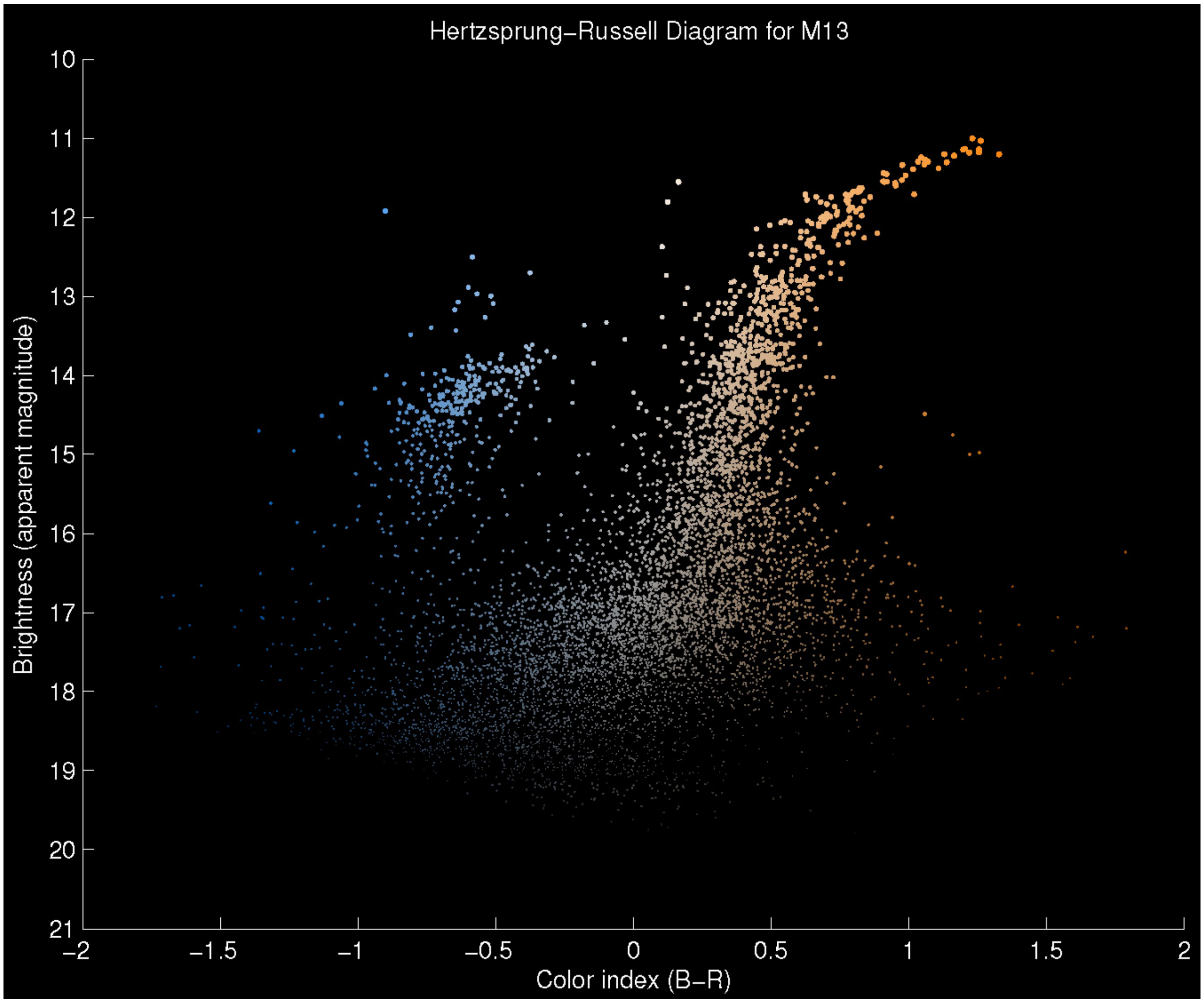
I like globular clusters so much that I tend to revisit my favorites each year and retake their picture. Hence, I can compare pairs of HR-diagrams of the same cluster taken at different times. In general, such a pair of diagrams should look the same. But, the RR Lyrae stars are variable and therefore can be expected to have slightly different brightnesses when imaged at two different times (even if taken just hours or days apart). To illustrate the RR-Lyrae stars, I modified my simple plotting program to read in two images of a single cluster and produce on one chart a combined HR-diagram. If a given star has about the same brightness in the two images, I simply plot a



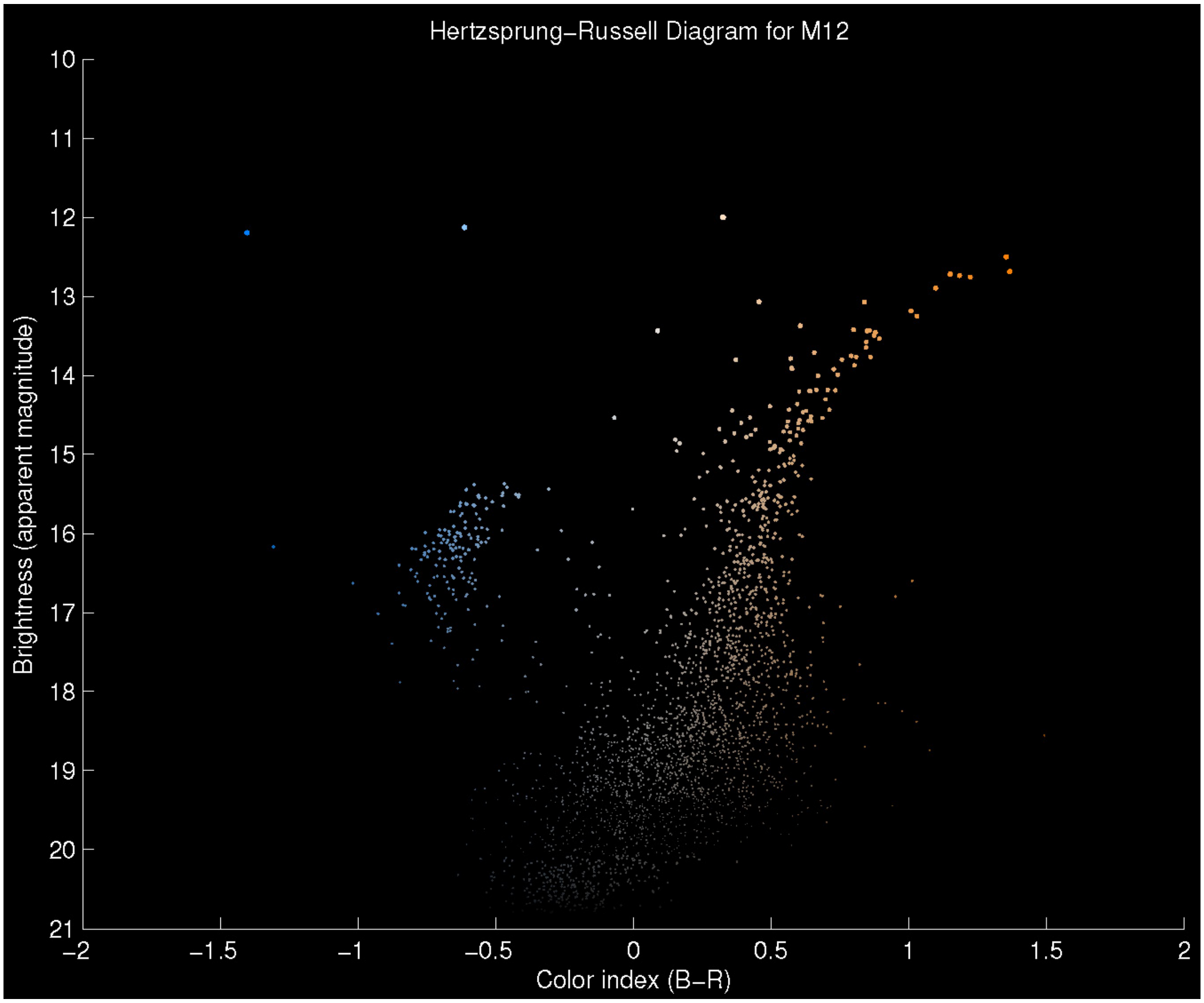
All stars in a globular cluster formed at the same time but with various initial masses. The arrows show the progression from lower mass stars to more massive ones.

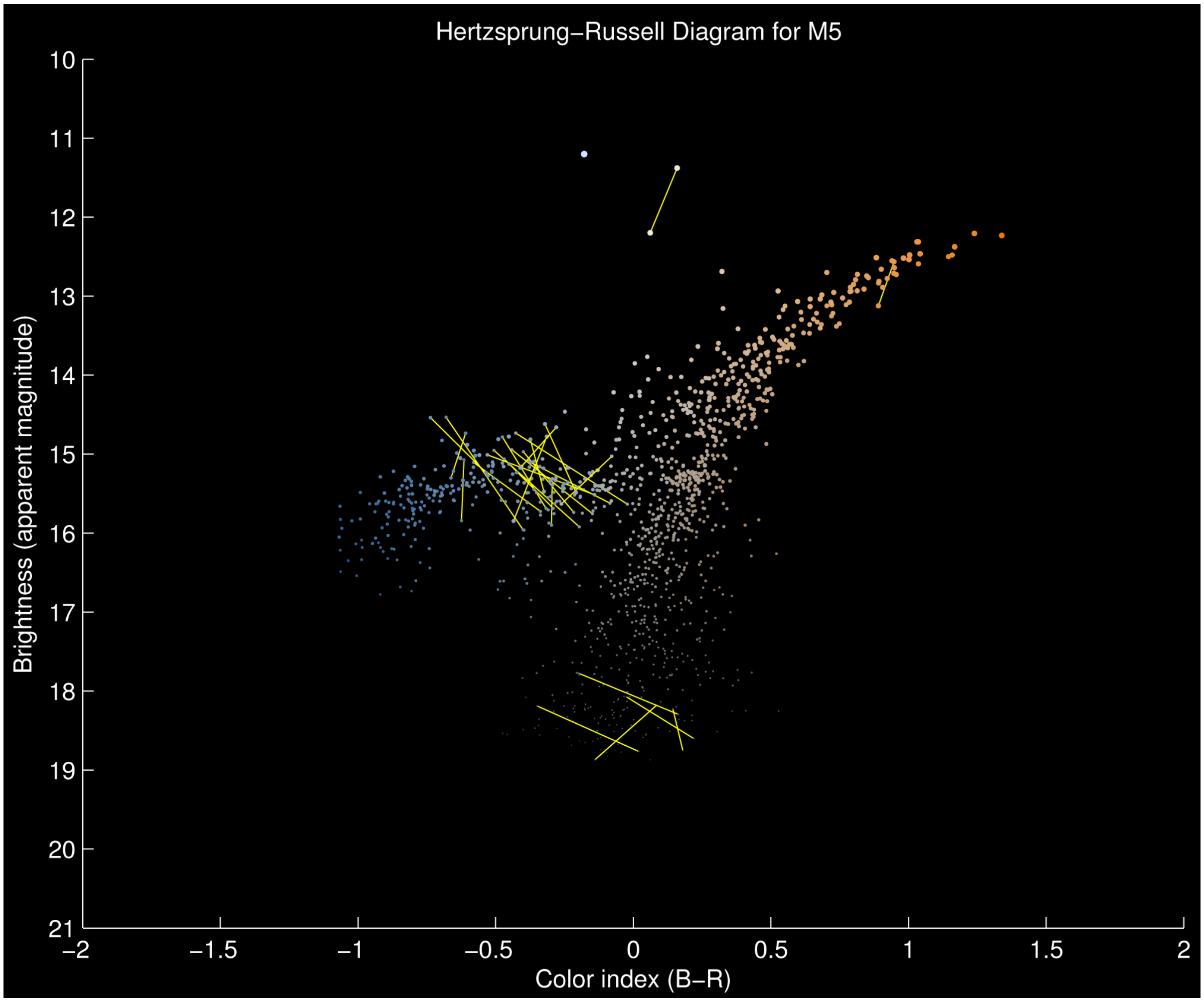
single point using the average of the two brightnesses and the average of the two colors. But, if the brightnesses are significantly different, I plot both points and connect them with a yellow line. Such an HR-diagram for M5 is shown here. The RR Lyrae stars are exactly where we expect them to be—on the horizontal branch. Some of the very faint stars, magnitude 18 and fainter, also get yellow lines. In these cases, however, the spread is much more likely a result of noise in the image data—these are, after all, very faint stars. The estimate of brightness and color is bound to be quite imprecise. Finally, one bright star not on the red-giant branch appears to be variable. It is probably a field star and perhaps it really is variable.

My full collection of HR-diagrams and the computer program I used to produce them can be found at http://www.princeton.edu/∼rvdb/images/NJP/HRdiagMatlab.html. As explained earlier, star colors and luminosities can be extracted from an image file using the freely available software program called SExtractor (http://www.astromatic.net/software/sextractor). Two other programs that will automatically extract all stars in an image are AstroArt (http://www.msb-astroart.com/) and Mira (http://www.mirametrics.com/). SExtractor and AstroArt produce plain text files listing data for each star.



Hertzsprung-Russell diagram created using the CCD images that produced the picture shown on the previous page.


Hertzsprung–Russell Diagram for M12
Brightness (apparent magnitude)
10
11
12
13
14
15
16
17
18
19
20
21
Color index (B–R)
–2
–1.5
–1
–0.5
0
0.5
1
1.5
2


Hertzsprung−Russell Diagram for M5
Brightness (apparent magnitude)
10
11
12
13
14
15
16
17
18
19
20
21
−2
−1.5
−1
−0.5
0
0.5
1
1.5
2
Color index (B−R)