Measuring the Distance to and Age of an Open Cluster

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Star clusters can serve as important tools to study the star formation, the dynamics of the ISM, and the evolution of our galaxy. They provide Astronomers the opportunity to study stellar populations where members might share many observational properties. These properties may include astrometry (space velocities, group dispersion), metallicity, and, pertaining this lab, distance and age.

This lab will introduce students to H-R diagrams, stellar clusters, and how different clusters might appear on these H-R diagrams. Additionally, we will explore how an H-R diagram might allude to the distance and age of a cluster, estimating the distance and age of the open cluster NGC 752.

1. The H-R Diagram

The OBAFGKM spectral classification system we know today was pioneered by Edward Pickering, the Harvard College Observatory director and Williamina Fleming, his housekeeper who rose to become a prominent astronomer due to her talents. The Pickering-Fleming system sorted thousands of stars based on their spectra, and was revised several times into its present form.

In the early 20^{th} century, two astronomers independently plotted stars' absolute visual magnitude against their spectral type. The Danish Ejnar Hertzprung and the American Henry Norris Russell found a clear correlation between a star's magnitude and spectral type. This kind of diagram is now known as a Hertzprung-Russell or **H-R diagram**. Figure 1 shows Henry Russell's original H-R diagram.

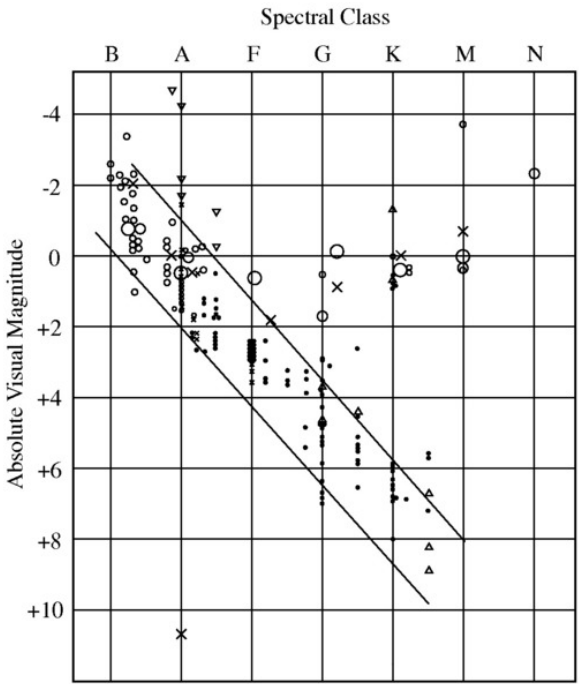


Figure 1. Henry Russell's original H-R diagram with absolute visual magnitude on the vertical axis, and spectral type on the top-vertical axis. Credits: Henry Norris Russell, *Relations between the spectra and other characteristics of stars*, Popular Astronomy 22, 275-294 (1914).

(a) Why that pattern?

The correlation the two astronomers observed was, of course, a relation between the luminosity (L) of a star and its effective temperature T_{eff}. The fact that stellar spectra, and thus spectral type, depended on the star's effective temperature was was understood even back in the 20^{th} century, so this absolute visual magnitude vs. spectral type relation makes sense. Stellar evolution theory explains this relationship by modelling the star after a similarly sized blackbody with the same power-output. On a tangent, this is why we specify an 'effective temperature' T_{eff} for a star—it is the temperature of the equivalent black body. In reality, stars have a wide range of temperatures depending on where we measure (although T_{eff} is a good approximation for a stars photosphere). The blackbody model of a star suggests the L—T_{eff} relation in Equation 1.1.

$$L = 4\pi R^2 \sigma T_{eff}^4 \tag{1.1}$$

Here σ is the Stefan–Boltzmann constant, and R is the stellar radius. This also clarifies why an H-R diagram may be plotted with a colour index (like $B - V$) on the x-axis instead of temperature. The colour index of a star is linked to its T_{eff}. Hotter stars tend to be bluer, while cooler stars are redder. Figure 2 shows how star luminosity changes with spectral class, colour, and temperature. Figure 3 shows an H-R diagram with stars within 100 pc of the Sun, made with measurements from the Hipparcos satellite.

(b) Apparent vs. Absolute Magnitude on Colour-Magnitude Diagrams

Let's say we have a set of random stars from all over the Milky Way. Let's see what happens when we try to make an H-R diagram using *apparent magnitudes* on the y-axis for this set. Figure

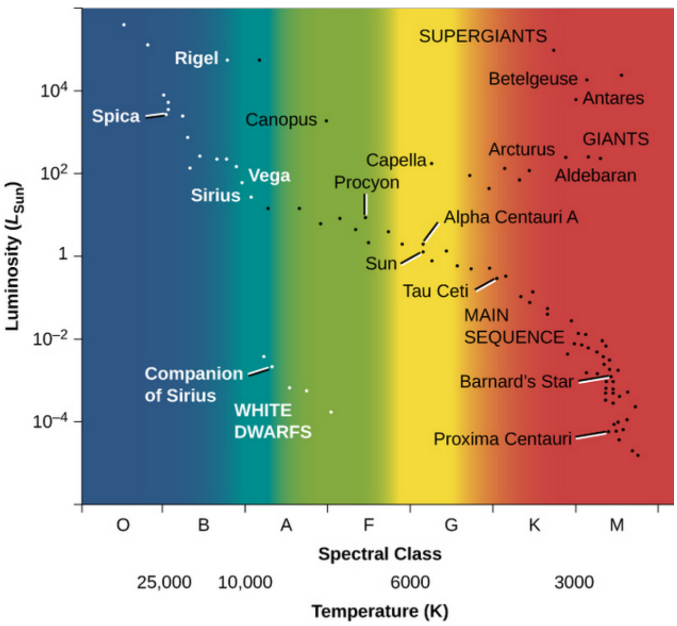


Figure 2. An H-R diagram displaying how stellar colour, spectral type, and temperature correlate and may be used on the x-axis. Credits: *Andrew Fraknoi et. al. OpenStax Astronomy.*

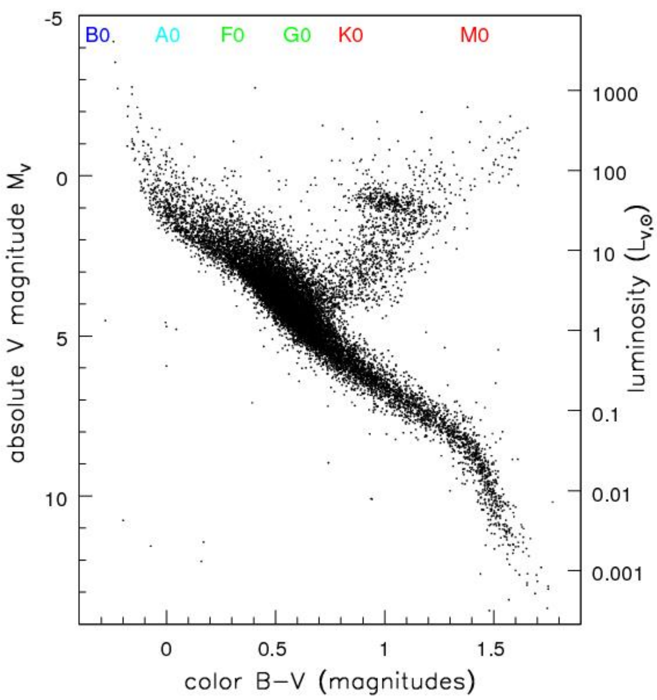


Figure 3. H-R diagram of stars within 100 pc with measurements from the Hipparcos satellite.

4 shows what such an H-R diagram might look like. Messy!

[Q] What changed? Why do we use the the *absolute magnitude* on the y-axis instead of *apparent magnitude* when plotting an H-R diagram for a set of stars?

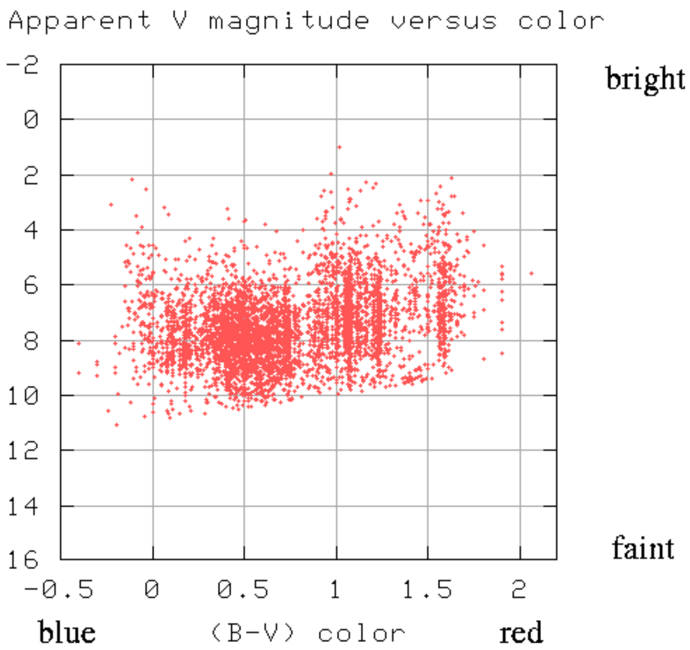


Figure 4. An H-R diagram for a set of stars at different distances. Quite random! Credits: *Michael Richmond, Rochester Institute of Technology.*

(c) What do H-R Diagrams Say?

H-R diagrams can tell us a lot about the stars that they include. The most prominent feature of the H-R diagram is indubitably the approximately linear pattern found from the top-left (hot, bright stars) to the bottom-right (cool, dim stars). This region is called the **main sequence**, and the vast majority of stars ($\sim 90\%$) reside here. One might ask, what determines where on the main sequence a star resides? A star's position on the main sequence generally depends on its mass. That kind of makes intuitive sense. More massive stars have their cores under greater gravitational pressure, leading to faster fusion, higher energy outputs, and greater temperatures. Less massive stars contend with less gravitational pressure, and hence burn their fuel slower.

But an H-R diagram might show more the main sequence. Figure 3 clearly shows a significant population of stars branching out from the main sequence towards the upper-right corner. These stars are **red sub-giants, giants, super-giants, and hyper-giants**. When a main sequence star depletes its hydrogen reserves, it begins to shift upwards and to the right of the H-R diagram. This means that the star's T_{eff} lowers while it simultaneously expands and its luminosity increases.

[Q] Why does a typical main-sequence star, when it transitions into a red star, increase in luminosity even though its T_{eff} decreases and hydrogen reserves deplete?

The H-R diagram shows us several more populations of stars residing in different locations due to their unique properties. Figure 5 shows several such locations.

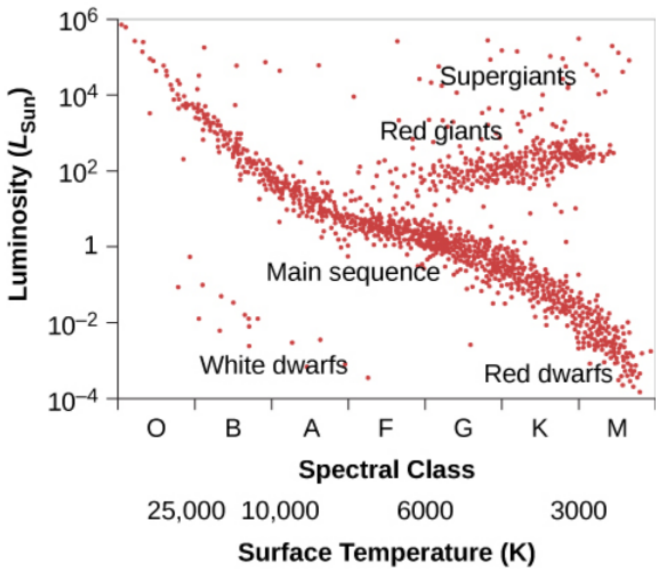


Figure 5. An H-R diagram displaying where different stellar populations reside in the H-R diagram. Credits: *Andrew Fraknoi et. al. OpenStax Astronomy.*

2. Clusters

What are star clusters? Believe it or not, astronomers aren't certain! They tend to have several definitions depending on how they're using clusters. Star clusters (not to be confused with galactic clusters (https://www.cfa.harvard.edu/research/topic/galaxy-clusters) can be broadly thought of a collection of stars born from the same gas cloud, bound together by gravity. Since these stars are near each other, their distance to us are roughly the same, and since they have been born around the same time, they share a common approximate age.

Clusters have historically been separated into open clusters (generally found within the disk of our galaxy) and globular clusters (usually residing in the galaxy halo). Open clusters are often young ($\sim 10^7$ yr), loosely grouped, and generally contain a few hundred members. Globular clusters, on the other hand, are generally older ($\sim 10^{10}$ yr) and quite dense, with tens of thousands to millions of stars packed within a ~ 10 Light-year radius. Figure 6 shows examples of open and globular clusters.

3. H-R Diagrams and Clusters

(a) Cluster H-R diagrams: Apparent and Absolute Magnitude

We've previously seen that plotting an H-R diagram with a set of random stars from around the galaxy while using apparent magnitudes on the y-axis gives us a very random scatter-plot. However, if we take a set of stars from a cluster and plot an H-R diagram with apparent magnitudes, we'd see a familiar H-R pattern.
[Q] Why does using apparent magnitude on y-axis for a set of random stars not yield a pattern, while doing the same with stars in clusters does?

Figure 6. The Pleiades (Left) is an open cluster about 400 Light-years from Earth and contains about 3,000 stars. The Hercules cluster (Right) is a globular cluster about 22,000 Light-years away and contains as many as a million stars. Image Credits: NASA, ESA, AURA/Caltech, Palomar Observatory (*Pleiades*), Sid Leach/Adam Block/Mount Lemmon SkyCenter *Hercules*.

[Q] Imagine you make two H-R diagrams from a set of stars in a far away cluster, one with apparent magnitude and the other with absolute magnitude. What difference would you see?

[Q] From the difference you might observe, how could you figure out the actual distance to the cluster? (Hint: learn about distance modulus at `https://astronomy.swin.edu.au/cosmos/d/Distance+Modulus`).

(b) ZAMS

What would we see if we got a bunch of stars in a cluster which have just been born, and plotted them on an H-R diagram? Figure 7 shows such an H-R diagram. It's pretty much linear and we don't that branch of stars moving away from the main sequence. Astronomers call this sort of H-R diagram the ZAMS (zero-age main sequence), which is an H-R diagram with every star in the main sequence. ZAMS are quite rare in reality, but we do see some ZAMS-like behaviours in some stellar populations.

[Q] Why do we observe all stars to be on the main-sequence for a young cluster?

[Q] Why could ZAMS be so rare?

(c) The Shapes of Cluster H-R Diagrams

We've discussed previously how H-R diagrams may show stars in different locations depending on their properties and on what stage of their evolution they might be on. Often, we are able to see the main sequence and the branch of stars which begin to move away from the main sequence to the upper-right corner after expending their hydrogen fuel reserves. Figure 3 shows this branch 'protruding' from a continuous main-sequence that is well defined from the top-left to the bottom-right. The H-R diagram for a cluster, however, can look a lot more different. Figure 8 shows the H-R diagram for the globular cluster 47 Tucanae. Can you see how the shape is different from Figure 3, the H-R diagram from the Hipparcos satellite?

I'm sure you'll have found many differences. One of the more prominent ones is that the main-sequence does not extend all the way to the top-left. Where did the hot, bright stars on the top-left of the main-sequence go? Additionally, the red-giant branch seems to originate from the end of

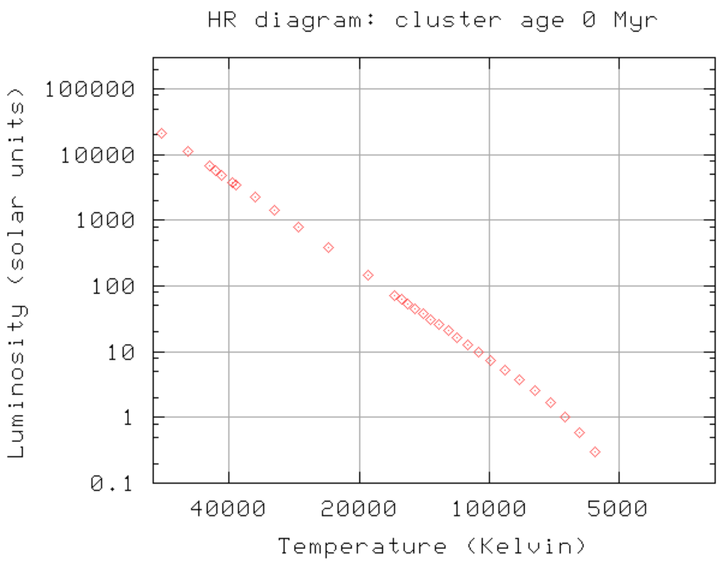


Figure 7. H-R diagram for a very new cluster. Credits: *Michael Richmond, Rochester Institute of Technology.*

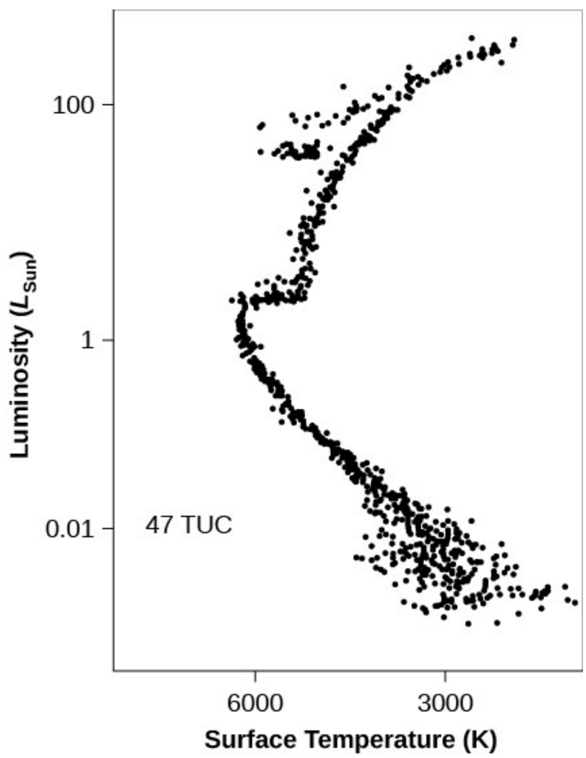


Figure 8. H-R diagram for the Cluster 47 Tucanae. Compare this to Figure 3, which displays the H-R diagram of stars within 100 pc of earth and that aren't all in one cluster. Credits: *Andrew Fraknoi et. al. OpenStax Astronomy.*

the main-sequence rather than somewhere in the middle. Incidentally, the point where the red-giant branch meets the main-sequence is called the **main sequence turn-off point**.

[Q] Why do we see these differences between Figure 8 and 3? (Hint: remember the aforementioned fact about ages of the stars in the cluster, and think about which stars transition into red-giants the fastest.)

(d) The Time Evolution of Cluster Stars

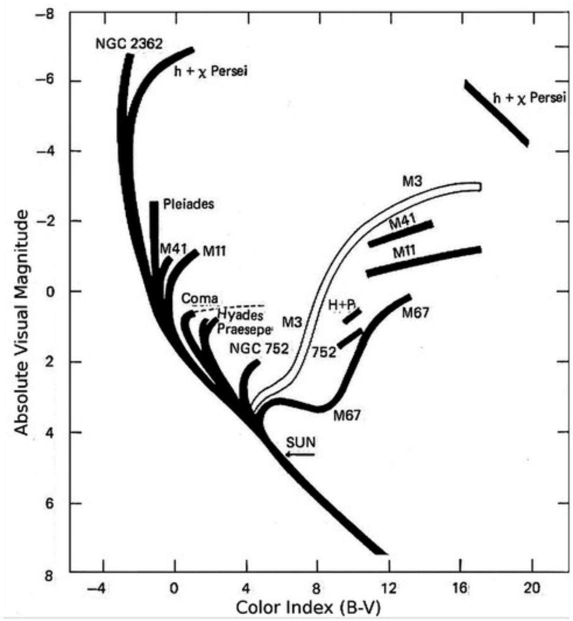
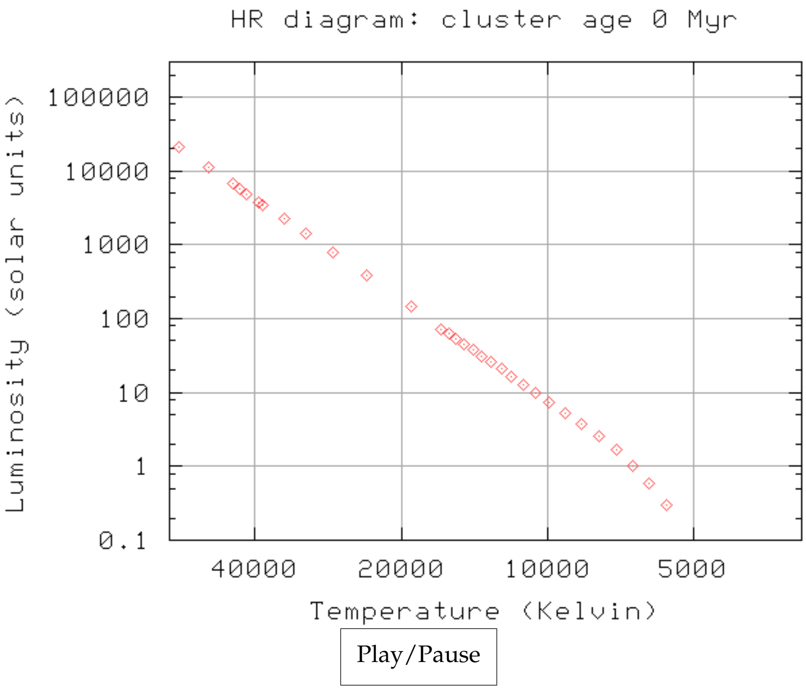


Figure 9. Several clusters being plotted on an H-R diagram. We can see that different clusters start to move away from the main sequence at different points. Credits: Alan Sandage *Astrophysical Journal 126, 326*, (1957).

Figure 9 shows the H-R diagrams for several different clusters. Among these is NGC 2362, which (approximately) displays the legendary ZAMS behaviour. Other clusters can also be seen with a very interesting variation—different clusters seem to have their main sequence turn-off at different points.

[Q] Why could this be? Professor Michael Richmond's excellent GIF, which shows a cluster's H-R diagram as it ages, might be helpful in thinking about this. (Open this lab file in a dedicated PDF program to make sure the GIF works.)



[Q] Having thought about the previous question, what is one way to figure out the age of a cluster?

4. Isochrones

A ZAMS can show us how a cluster might look on an HR diagram when it is young. However, it can't tell us how a cluster may look when it is at different ages, and we might be really interested in knowing that as many clusters are at different points in their evolution. If we could now how a cluster might look at different times. That's where isochrones come in. Astronomers can create H-R diagrams for how clusters may evolve through time by using theoretical models taking into account a cluster's population, kinematics, metallicities, dust extinction, and atmospheric models. Many of the professional models astronomers use are complex and computationally expensive to compute. That's why a lot of these available pre-processed on dedicated astronomical servers! A popular stellar evolution and population synthesis code is Modules for Experiments in Stellar Astrophysics, or MESA. MESA documentation may be found at https://docs.mesastar.org. From this code base, a Harvard team has created MESA Isochrones Stellar Tracks, or MIST (https://waps.cfa.harvard.edu/MIST/), dedicated to creating and hosting isochrones and stellar evolutionary tracks for populations with a wide range of properties.

MIST isochrones and tracks are widely used by professional astronomers to calculate the age of star clusters. In fact, you will soon be using MIST codes to find out the age of your own cluster!

Acknowledgment

This lab was created with media and images from a wide range of sources. In particular, Michael Richmond's *Interpreting the HR diagram of stellar clusters* (licensed under Creative Commons CC BY-NC-SA 2.0) provided informative graphics. The OpenStax Astronomy textbook (Andrew Fraknoi, David Morrison, Sidney C. Wolff et. al.) provided diagrams and is referred for further reading. Stellar isochrones from MIST were utilised in this lab. Photometric data for NGC 752 was obtained from the Photometry and radial velocities in NGC752 (Daniel+, 1994) data collection on VizieR. Photometric data for M53 was obtained from the BV photometry of M53 (Rey+, 1998) data collection on VizieR. This document was built upon the Royal Society Open Science Overleaf template, which is licensed under Creative Commons CC BY 4.0.

References

1. Adamo, A., Zeidler, P., Kruijssen, J. M. D. et. al. 2020 *Star Clusters Near and Far; Tracing Star Formation Across Cosmic Time*. Space Science Reviews *2020SSRv..216...69A*
2. Dotter, A. 2016 *MESA Isochrones and Stellar Tracks (MIST) 0: Methods for the Construction of Stellar Isochrones*. The Astrophysical Journal Supplement Series *ApJS..222....8D*
3. Choi, J., Dotter, A., Conroy, C. et. al. 2016 *Mesa Isochrones and Stellar Tracks (MIST). I. Solar-scaled Models*. The Astrophysical Journal *2016ApJ...823..102C*
4. Daniel, S. A., Latham, D. W., Mathieu, R. D. et. al. 1994. *A Photometric and Radial-Velocity Analysis of the Intermediate-Age Open Cluster NGC 752* Publications of the Astronomical Society of the Pacific *1994PASP..106..281D*
5. Paxton, B., Bildsten, L., Dotter, A. et. al. 2011 *Modules for Experiments in Stellar Astrophysics (MESA)*. The Astrophysical Journal Supplement Series *2011ApJS..192....3P*
6. Paxton, B., Cantiello, M., Arras, P. et. al. 2013. *Modules for Experiments in Stellar Astrophysics (MESA): Planets, Oscillations, Rotation, and Massive Stars* The Astrophysical Journal Supplement Series *2013ApJS..208....4P*
7. Paxton, B., Marchant, P., Schwab, J. et. al. 2015. *Modules for Experiments in Stellar Astrophysics (MESA): Binaries, Pulsations, and Explosions* The Astrophysical Journal Supplement Series *2015ApJS..220...15P*
8. Paxton, B., Schwab, J., Bauer, E. B. et. al. 2018. *Modules for Experiments in Stellar Astrophysics (MESA): Convective Boundaries, Element Diffusion, and Massive Star Explosions* The Astrophysical Journal Supplement Series *2018ApJS..234...34P*
9. Rey, S., Lee, Y., Byun, Y. et. al. 1998. *CCD Photometry of the Globular Cluster M53. I. Color-Magnitude Data and Blue Straggler Stars* The Astrophysical Journal *1998AJ....116.1775R*