A Star is Born: Visualizing Stellar Evolution

Process Book

Image credit: NASA JWST

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CS 6630 - Visualization For Data Science

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I. Overview

A Star is Born: Visualizing Stellar Evolution is an interactive visualization designed to present engaging, interactive visuals that explain a star cluster's development through its lifetime. The website is geared towards a general audience, thus the scientific background is presented at a novice level.

Stellar evolution is the process by which a star changes throughout its lifetime. The lifetime of a star is dictated by the mass of a star. A star's life trajectory is predestined by mass because the mass determines how much energy a star can produce and how quickly it will burn the energy. More massive stars can have lifetimes of around a few million years, whereas smaller stars can live on the order of trillions of years. All stars begin their lives from a gravitational collapse of giant molecular clouds of gas and dust. These molecular clouds are often referred to as nebulae. Stars like these, still in their early stages of gathering gas and dust, are called protostars. Over the next millions of years, protostars gradually reach a state of equilibrium, becoming main-sequence stars.

For a majority of its lifespan, a star derives its energy from nuclear fusion. Initially, this energy results from the fusion of hydrogen atoms within the core of main-sequence stars. As the core accumulates more helium, stars (like our Sun) transition to fusing hydrogen in a spherical layer surrounding the core. As this process progresses, it leads to a gradual increase in a star's size, where it passes through the next stage of its life: the subgiant phase. Subgiant stars continue to accumulate mass into the red giant phase.

Stars with at least half the mass of the Sun can also produce energy by using helium in their core, while more massive stars undergo fusion of heavier elements across concentric shells. When a star akin to the Sun exhausts its nuclear fuel, its core collapses into a dense white dwarf, and the outer layers are ejected, forming a planetary nebula.

Stars with roughly ten times the mass of the Sun (or more) can undergo a supernova explosion when their inert iron cores collapse, resulting in the formation of an incredibly dense neutron star or black hole. Although the universe has not yet witnessed the end of the lifespan of the smallest red dwarfs, stellar models predict that they will gradually become brighter and hotter before depleting their hydrogen fuel and evolving into low-mass white dwarfs.

The Hertzprung-Russell (H-R) diagram, as seen in Figure 1, is an important tool for understanding stellar evolution. This plot shows the surface temperature vs luminosity of a star cluster. As a star goes through changes in its lifecycle, it follows a characteristic path moving to different regions of the H-R diagram, which is dependent on the chemical composition and mass of the star. The mass and age of stars are difficult to measure directly, therefore astronomers can use temperature and luminosity to indirectly determine the masses and ages of stars. Throughout a star's lifetime it will change positions on the H-R diagram. The H-R diagram will be the heart of this work. We want to create an interactive H-R diagram that allows users to see where stars appear on the H-R diagram as they evolve throughout time. Stars live for much longer than humans have existed, thus to generate a population of stars evolving over time, we must generate theoretical data.

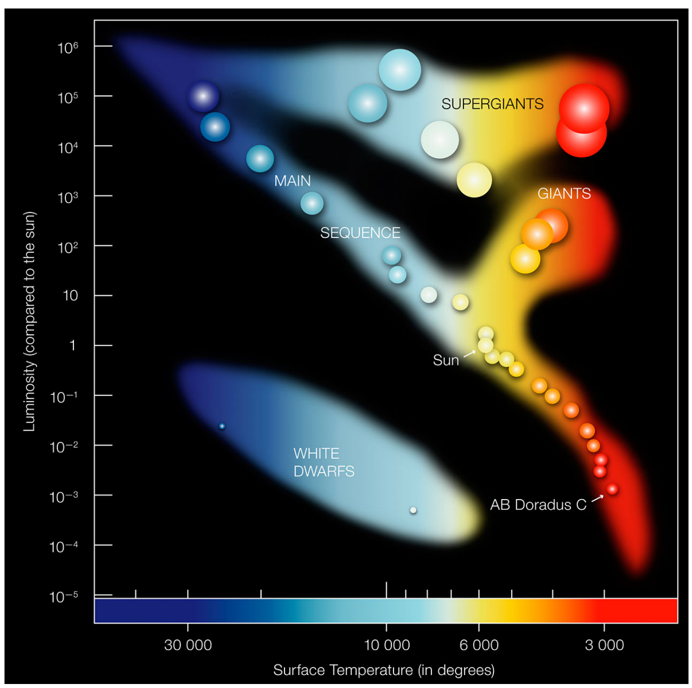


Figure 1: Example of a Hertzsprung-Russell (H-R) diagram. It shows the relationship between stellar surface temperature and luminosity. The colors are indicative of the surface temperature where reds and yellows are cooler stars and blues are hotter stars. Credit: ESO

Looking at just one population of stars with the same age but different masses represents an isochrone. Astronomers can generate simulations of stars, provided some parameters, to create a population of stars. Isochrones produce the distinct curve that we see in the H-R diagrams. They are closely related to the H-R diagrams because we predict that the stars in the cluster plotted on the diagram have relatively the same age, producing the signature curve. Astronomers can compare theoretical isochrones to the observed data to estimate the age of the clusters. In Figure 2 below, seven isochrones are shown. The left-most black line represents the youngest stellar population known as the zero-age main-sequence. The ages increase moving right in the intervals specified on the plot.

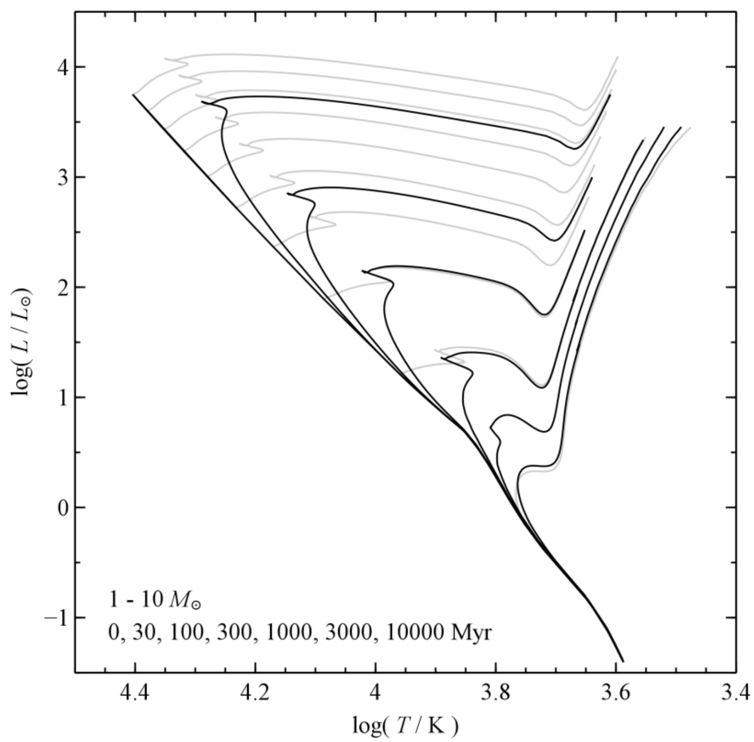


Figure 2: Example of isochrones. Tracks for each mass track can be interpolated to a specific age to generate an isochrone, or population of stars with the same age but varying masses. The left-most black line is the youngest population, 0 Myr, and the ages increase moving to the right according to the key on the plot.

II. Motivation

We initially prepared to work on a project incorporating climate data. After scrolling through previous works, we challenged ourselves to brainstorm a more original project. We selected this project based on a combined interest in astronomy/astrophysics and the fact that at least one member of the group actively works on particle astrophysics research in their graduate work. A few of our initial ideas were to create some kind of evolution of the Universe, galaxy evolution, and interactive plots characterizing different types of stars. Through the spit-balling of ideas, we began narrowing down to working with stellar data. We were excited about the idea of creating an astronomy-based visualization project as the public tends to find astronomy flashy and interesting. Through this project, we hope to become more familiar with stellar evolution and implement visualization techniques learned throughout the course.

For the purpose of this project, we decided to hone in on what kind of visualizations we wanted to create rather than answer larger research questions.

Science communication is a crucial component of being an effective scientist. In particular, communicating abstract ideas that are not intuitive for general audiences to understand gives rise to the necessity for creative, interactive, and informative visualizations. Astronomy is special because the general public can see its influence regularly. From directly looking up into the sky, to government-funded agencies, media, ancient nomadic methods of travel, and space exploration dating back to the 1950s.

Related Work

A culmination of sources went to the inspiration for our project. Initially, we aimed to create interactive maps of climate data, but found that had been done many different ways in previous projects. Looking through previous years' project submissions, one project in particular piqued our interest. *Visualization of Mesozoic Dinosaur Evolution* sparked our inspiration for doing an astronomy-based evolution project. We also liked their use of the data tree to show different kinds of dinosaurs from different eras, which eventually evolved into being incorporated into our star project.

From there we tossed around different ideas of cosmic evolution, galactic evolution, and finally landed on the evolution of stars. We knew that the H-R diagram would need to be the centerpiece of our webpage, but did not want to have a static plot, but something that users can interact with and see what ages of stars grow to which section of the H-R diagram in their lifetimes, and the characteristics of those stars at that time. A Google search for visualizations for stellar evolution brought us to Aaron M. Geller, an astronomer and visualization specialist from Northwestern University. Dr. Geller has a page packed with WebGL and D3 physics and astronomy interactives. Geller's Dynamical Evolution of a Star Cluster was the main inspiration that led to what will be the heart of our project. He implemented a H-R diagram that evolves in time via an interactive timeline. Additionally, he created a model of the dynamical evolution of the star cluster through time, which shows how the star cluster orbits around the galaxy and how the stars interact gravitationally. Examples of Geller's visualizations are below.

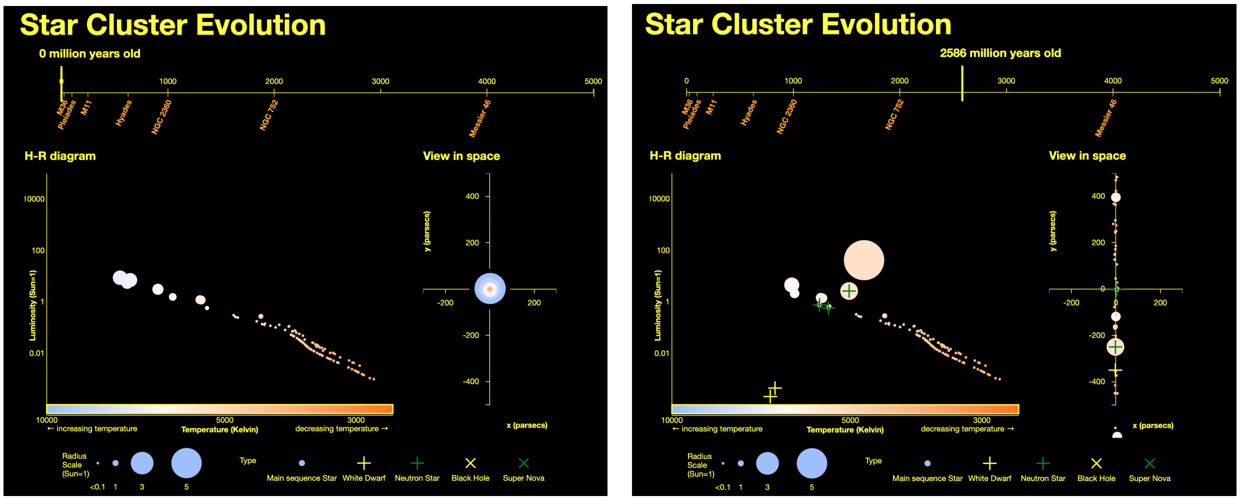


Figure 3: Screenshots of Geller's Dynamical Evolution of a Star Cluster work. The star cluster is shown at age 0 (left) and how the cluster evolves after ~2.5 million years (right). On the right side of each figure, Geller creates a visualization that shows how the stellar masses move over time as well. In the left panel the masses are congregated in one spot and over time they move due to gravitational pull and orbiting through the host galaxy.

Another important visualization in this work will be the stellar evolutionary track tree. We are working to design a tree that expands to show evolutionary different tracks that stars can take, which is dependent on their initial mass acquired in the protostar phase. The root node of the tree will be the molecular cloud, then expand into the protostar phase, which all stars experience, and branch into three different tracks. Our tree will be based off the following graphic:

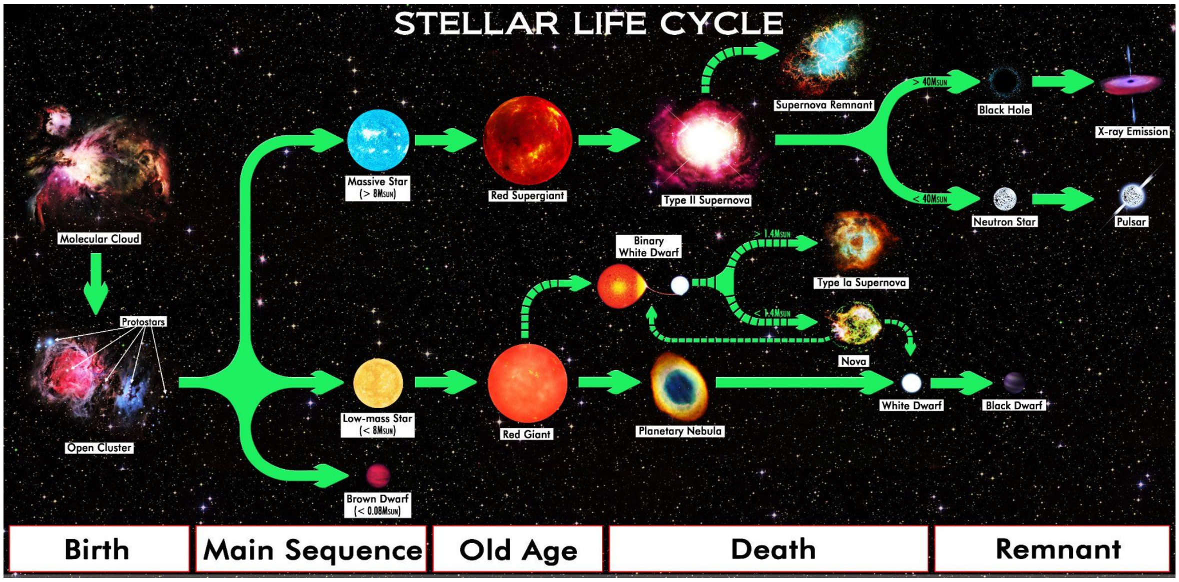


Figure 4: Example of the stellar evolution tree we aim to build. Credit: R.N. Bailey - Own work, CC BY 4.0

Questions

Stellar evolution is a well studied sector of astronomy, thus our approach to this work was untraditional. Once we had an idea of what we wanted to create, our focus was shifted more towards what kind of interesting and interactive visualizations can we create with a specified set of data. In other words, we first began envisioning the kind of visualizations we wanted to display and the elements we have learned in the course that we wanted to incorporate, found a few datasets that have the information we need, then sought out what questions users would be asking when using our tool.

Our main goal for this project is to produce an informative and dynamic visualization to effectively communicate the stellar evolution process for general audiences. We had several initial questions that have changed as our project has been developing. To achieve our overarching goal, we first ask what are the foundational components to understanding how stars evolve. This question was simple: astronomers use H-R diagrams. Next we ponder how we can make traditionally static plots used for scientific investigation engaging. From our personal experiences, we know that users enjoy vibrant color schemes and interactiveness while maintaining a certain level of simplicity so users do not become overwhelmed with information.

We want to highlight the user experience and turn the attention to how users interact with the visualization and what questions they may ask. With our three different visuals, we expect some of the following questions.

- What is the luminosity and temperature of a particular star?
- Where does our Sun or a sun-like star appear on the H-R diagram?
- Where do other kinds of stars (red giant, white dwarf, super giant, etc.) appear in the H-R diagram and what are the characteristics of those stars?
- What does the lifecycle of a particular type of star look like?
- How do different properties of stars relate to each other?
- What are different evolutionary tracks that stars can take?
- What are the different stages of a star's lifetime?

Data

To our surprise, the data has been the most challenging obstacle to overcome throughout this project. We proposed to use data from Gaia. Gaia is a space telescope run by the European Space Agency (ESA) that measures position, distance, and motion of stars with extraordinary precision. It is a global astronomy mission, working to catalog the largest, most precise picture of our galaxy. Gaia data is well published data in that it is mostly clean data, which was our motivation for selecting to work with it.

However, we ran into problems using observational data. Using real data for stars introduces a lot of issues with assigning properties to those stars. In theory, we could start with a sample from the Gaia dataset and assume properties, but it still takes a lot of data cleaning to have a population of stars that looks coeval, which is beyond the scope of this project. Alternatively we are going to generate a synthetic H-R diagram using isochrones as input, and then “evolving” those using the same isochrones. To get stars with a wide range of masses and evolutionary stages, we are going to use Modules for Experiments in Stellar Astrophysics (MESA) Isochrones and Stellar Tracks (MIST). This will produce a grid of stellar models generated using MESA stellar models. Additionally, to generate a more sophisticated model we can make use of an initial mass function (IMF). This will ensure that we have significantly fewer high mass stars compared to low mass stars, which may be a desirable feature to show users more realistic populations. Isochrones tend to generate a single tight sequence of stars, but by introducing artificial uncertainties and scatter by choosing errors from a Gaussian centered on the original model value will spread out the model distribution. This procedure is known as simple stellar population synthesis. (Feiden et al. 2021) and is standard in the astrophysics field.

To do some preliminary work with isochrone data, we searched for smaller alternative datasets. We came across the Padova CMD data source created by a group of astrophysicists from Italy. The data is open source and allows users to select different stellar properties, catalogs of data, among various other parameters to tailor data for specified analysis. However, this data is still observational data and we require specific parameters to create a more complete evolutionary track of stars from a population.

Links to sources of data:

1. Padova: http://stev.oapd.inaf.it/cgi-bin/cmd_3.7
2. MIST: https://waps.cfa.harvard.edu/MIST/index.html
3. MESA: https://docs.mesastar.org/en/release-r23.05.1/
4. Gaia: https://gea.esac.esa.int/archive/

Exploratory Data Analysis

To explore our data, we first wanted to attempt to produce a sample H-R diagram using Gaia data. Upon further research of stellar data and rethinking our overall goal to have the stars evolve in time, we realized that observational data was not the route we needed to take as explained above. We realized we needed to gather a grid of isochrones, or stars of the same age but varying mass to have the stars evolve in time. To create the grid, we need to find the appropriate number of isochrone data to be able to evolve these in time to make it appear as a complete evolution. This is our final step in completing the data analysis and is still a work in progress. The data analysis was performed in Python using matplotlib.

With the Padova data, we generated sample plots of isochrones. Below are a few example plots. The x-axes are all the surface temperatures of the stars measured in Kelvin (K). The y-axis in each plot represents the luminosity measured in solar luminosity (L_sun), which is a unit of photon flux.

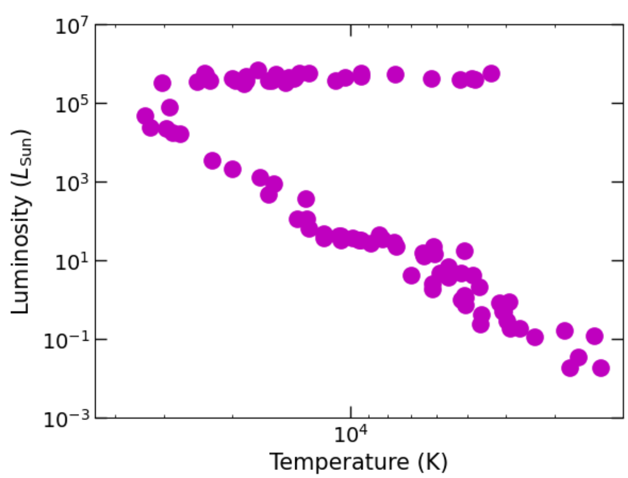


Figure 5: Step one was to create an isolated isochrone.

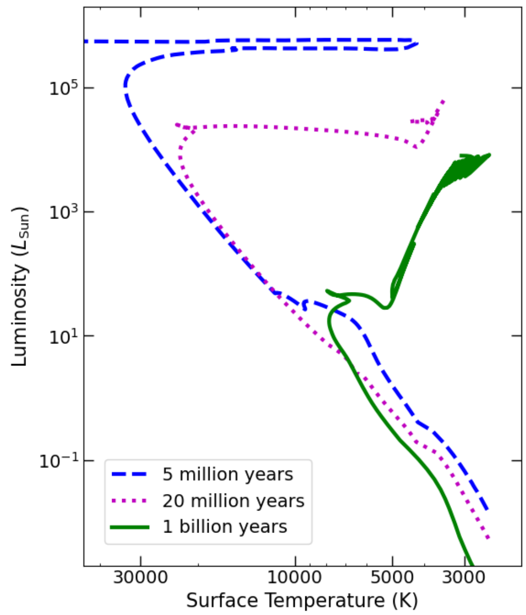


Figure 6: Example plot using Padova data to generate isochrones. These are stellar populations that have the same age at 5, 20, and 100 million years, but have different masses to produce the characteristic curve.

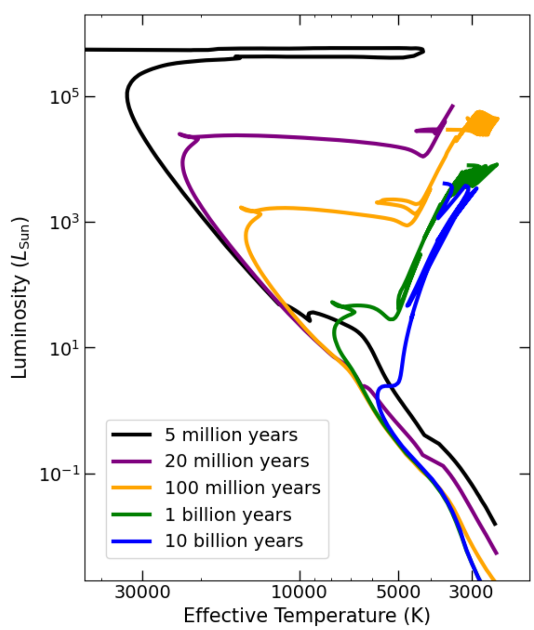


Figure 7: Example plot using Padova data to generate isochrones at several ages with different masses.

Design Evolution

Different visualizations that we have considered have been the data tree structure, scatter plots, and interactive plots. We have not yet drastically deviated from our proposal as we had an expectation of what our data would look like because we are reproducing well-known images with various populations of stars. However, we have adjusted more appropriate color palettes, which are still a work in progress.

Throughout this work, we have implemented many topics discussed in lecture. This work is task-driven as we are creating a new visualization from a bottom-up approach. We will implement visual encoding in the H-R diagram. Stars are spherical objects in nature, thus our data points will be in the shape of circles. We will also encode a to-scale size of each star relative to the size of our Sun. Additionally, the stars will be color-coded to indicate temperature. Cooler stars will be reds, oranges, and yellows, and hotter stars will be blues and whites. We have also tried to maintain graphical integrity to clear and detailed visualizations while still being effective in presenting the most relevant information.

Implementation

At this stage, our project has the main skeletal structure. We have the designated areas for each visualization on our page. The stellar evolution tree outline is in place and ready for images of each phase and the corresponding details, which are outlined below. For the H-R diagram, there is sample data in place to ensure that it is ready once the isochrone grid data is ready. The background of the page was created by manually generating “stars” (white points) and adding the parallax effect. We need to adjust color schemes, fonts, and interactive tools.

Features to still be implemented:

For the stellar evolution tree, the following images and descriptions still need to be implemented to the skeleton structure. We expect that when a user selects a branch of the tree the image will pop up with a brief description of the selected phase.

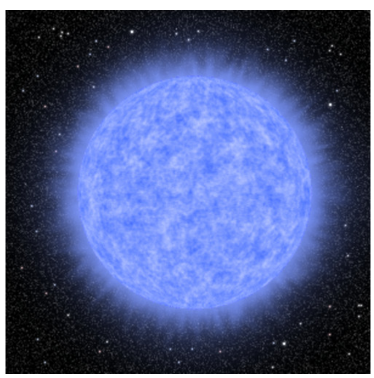
- The root of the tree is the **molecular cloud**. They are often referred to as “stellar nurseries” because this is the birthplace of stars. These interstellar clouds of gas, dust, and plasma. Regions of molecular clouds that collapse under the force of gravity begin to produce tiny planets to giant stars.


Credit: astrobites

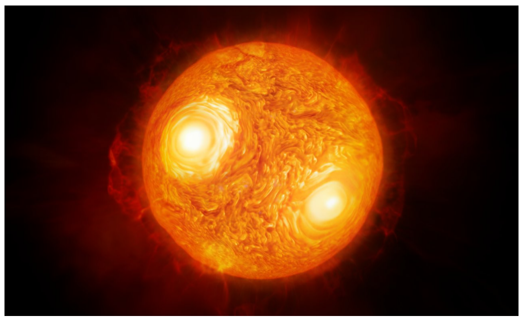
- **Open cluster:** The gravitational collapse of gas and dust pushes the stars to the next stage in a star's lifetime, which occurs in an open cluster. An open cluster is a star cluster composed of tens to thousands of stars. These stars formed from the same molecular cloud and are roughly the same age. The stars here are protostars or very young stars that are still accumulating mass from the molecular cloud. Pictured here is one of the most famous open clusters: the Pleiades cluster, also known as the seven sisters.


Credit: Smithsonian

- **BRANCH 1**
  - **Massive Star** (>8 solar masses (M_sun): Massive stars have masses that are greater than eight solar masses - that's eight times more than our Sun. They are typically some of the brightest stars in the night sky. It takes a lot of energy for massive stars to burn, thus they live very fast and die hard.


Credit: Florida Tech

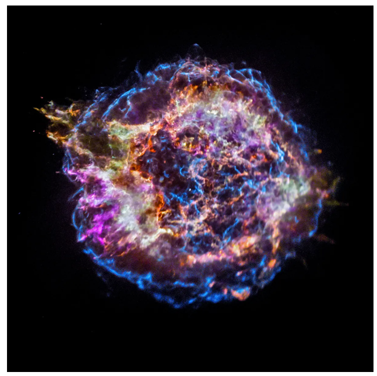
- **Red Supergiant:** Red supergiant stars are some of the largest stars in the Universe that are approaching later years in their life. Their size is hundreds to thousands of times greater than the Sun. Their red color is indicative of their cooler temperature. These stars burn heavier elements until they develop an iron core, which results in a supernova explosion.


Credit: ESO

- **Type II Supernovae:** The death of stars with masses between 8 and ~50 solar masses result in a rapid collapse and violent explosion known as a supernova. Type II supernovae in particular are distinguished from other supernovae by their hydrogen abundance.

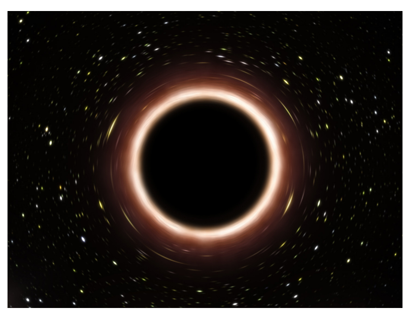

Credit: Max-Planck

- BRANCH 1.2:
    - **Supernova remnant:** Supernova remnants (SNR) are the structures leftover from explosions of stars that result in supernovae. SNRs consist of the ejected material expanding from the explosion. They are key components to understanding the ecology of galaxies.



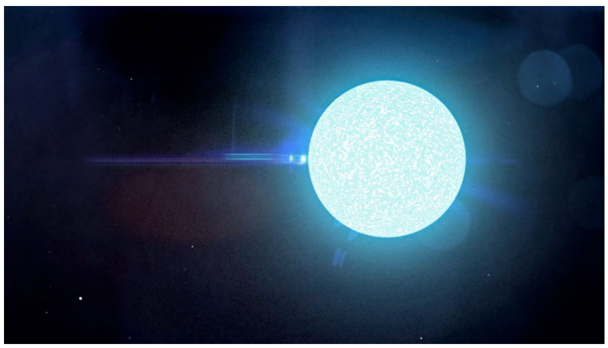
Credit: NASA

- BRANCH 1.3
    - **Stars** >**40 solar masses -> Black Hole:** A black hole is a region in space that is so dense, there is so much matter in such a small area, which causes the gravitational pull to be so strong that nothing can escape - not even light.

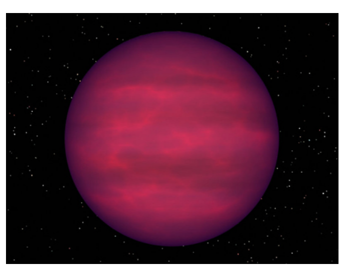


Credit: ESO

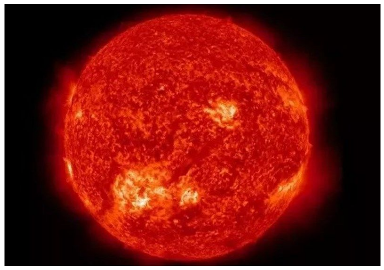
- **Stars <40 solar masses -> Neutron Stars:** Neutron stars are collapsed cores from supergiant stars. They are the result from supernova explosions combined with gravitational collapse. Aside from black holes, they are the densest known objects in our Universe. Once a star collapses into a neutron star it no longer generates heat and begins to cool over time. They typically have a radius of about 10 kilometers and mass of ~1.4 solar masses.


Credit: ScienceNews

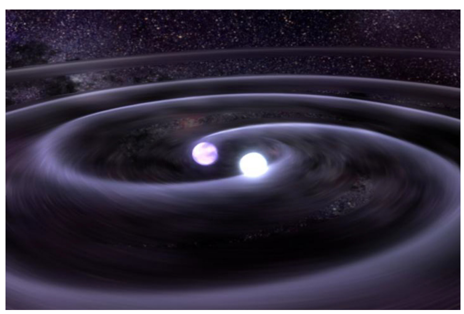
- BRANCH 2:
  - **Low Mass Star (<8 solar masses):** Low mass stars are stars that are less than 8 solar masses. They spend most of their life fusing hydrogen and helium in their core, which causes them to be the longest lived energy-producing objects in the Universe. Low mass stars are the most abundant, most difficult to detect, and can live for trillions of years.


Source: Caltech

- **Red Giant:** A red giant forms after a star has run out of hydrogen fuel for nuclear fusion, and has begun the process of dying. The atmosphere is inflated making the radius large but the temperature low.


Credit: The Planets

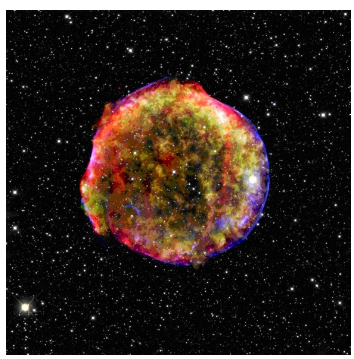
- BRANCH 2.1:
    - **Binary White Dwarf:** White dwarf binary stars are extreme systems that radiate gravitational waves as they orbit each other. To balance the loss of this energy, the stars gradually come closer together until eventually they merge. Many white dwarf binaries will explode as supernovae when they merge, but this newly discovered one is too small to trigger such an explosion. Instead, it will probably start fusing its helium atoms, and when it does - in about 37 million years - it will shine like a normal star again.


Credit: CfA

- BRANCH 2.1.1:
- **Stars >1.4 solar masses: Type Ia Supernova** is a type of supernova that occurs in binary systems (two stars orbiting one another) in which one of the stars is a white dwarf. The other star can be anything from a giant star to an even smaller white dwarf.


Credit: NASA

- **Stars <1.4 solar masses: Nova** an explosion from the surface of a white-dwarf star in a binary star system. A nova occurs when the white dwarf, which is the dense core of a once-normal star, steals gas from its nearby companion star. When enough gas builds up on the surface of the white dwarf it triggers an explosion.


Credit: Chandra

- **Binary white dwarf** is what stars like the Sun become after they have exhausted their nuclear fuel. Near the end of its nuclear burning stage, this type of star expels most of its outer material, creating a planetary nebula. Only the hot core of the star remains.


Credit: Caltech

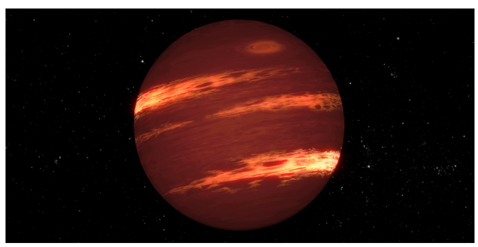
- BRANCH 2.2:
  - **Planetary Nebula** is a type of emission nebula consisting of an expanding, glowing shell of ionized gas ejected from red giant stars late in their lives. The term "planetary nebula" is a misnomer because they are unrelated to planets. All planetary nebulae form at the end of the life of a star of intermediate mass, about 1-8 solar masses. It is expected that the Sun will form a planetary nebula at the end of its life cycle. They are relatively short-lived phenomena, lasting perhaps a few tens of millennia, compared to considerably longer phases of stellar evolution.


Credit: ESA/Hubble

- **White dwarf** is what stars like the Sun become after they have exhausted their nuclear fuel. Near the end of its nuclear burning stage, this type of star expels most of its outer material, creating a planetary nebula. Only the hot core of the star remains.


Credit: Space

- BRANCH 3:
    - **Brown Dwarf (<0.08 solar masses):** (also called failed stars) are substellar objects that, while more massive than the most massive gas giant planets, are (unlike a main-sequence star), not massive enough to sustain nuclear fusion of ordinary hydrogen into helium in their cores.

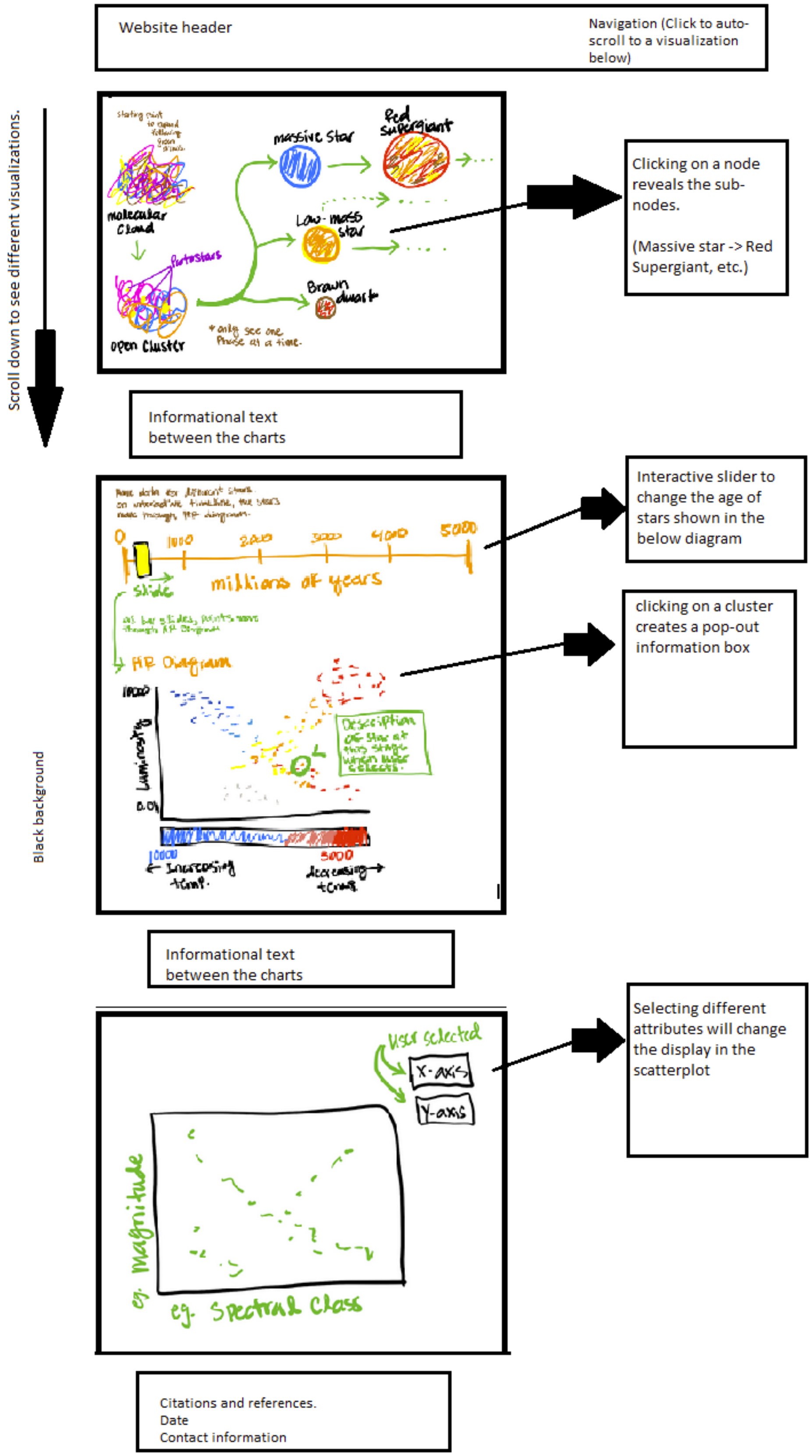

Credit: JWST

For the interactive H-R diagram, we still need to generate the grid of isochrones to show how stars evolve through time. Once we have created that data set, we can add the data to the placeholder. Then we need to implement the interactive timeline.

Our last visual, the interactive scatter plot, will be based on the data generated for the H-R diagram. It will be a simple scatter plot that allows users to select which stellar properties they would like to compare. Properties options will be mass, luminosity, temperature, radius, color, age, and metallicity. The plot will have a smooth transition for users to investigate how properties relate to each other.

Aside from our visualizations, we have a few final touches on the rest of the layout. We would like to have a vibrant color palette that suits the rest of our images while maintaining accessibility. We would also like to have our two main visualizations transition with each other. For example, if a user selects a supergiant star on the H-R diagram, the tree expands to show where in the stellar evolution tree the star appears.

We expect the final presentation to be organized as the following image:


Website header
Navigation (Click to auto-scroll to a visualization below)
Scroll down to see different visualizations.
massive Star
Red Supergiant
molecular Cloud
Protostars
Low-mass star
Brown dwarf
open Cluster
*only see one Phase at a time.
Clicking on a node reveals the sub-nodes.
(Massive star -> Red Supergiant, etc.)
Informational text between the charts
0
1000
2000
3000
4000
5000
slide
millions of years
HR Diagram
Luminosity
Description of star at this stage when user selects.
Increasing temp.
decreasing temp.
Interactive slider to change the age of stars shown in the below diagram
clicking on a cluster creates a pop-out information box
Black background
Informational text between the charts
User selected
X-axis
Y-axis
eg. magnitude
eg. Spectral Class
Selecting different attributes will change the display in the scatterplot
Citations and references.
Date
Contact information

Evaluation

By using our initial data, we learned that we had some misconceptions on how we were trying to execute the implementation of a time-evolving H-R diagram. H-R diagrams consist of stars of varying age and mass, thus we could not put all data points, or stars, on a shared timeline. If we used such data, we could take a couple different routes: significant amounts of data cleaning to search for stars in multiple massive catalogs to find stars of the same age and making assumptions about the data or implement many interactive timelines for a handful of stars, which would create a messy and confusing visual. Instead, we learned we could use theoretical data for stellar isochrones, which is data of a certain population of stars that all have the same age, but varying mass. If we stitch together a grid of isochrones to have the stars at different ages throughout their lifetime, we can see how they evolve through time. This has been the largest block in the progress of the project, but once realized, we have a clear path forward to complete this work.

At this stage, it is difficult to properly evaluate our visualizations because the proper data is not in place yet. However, we are optimistic about the outcome of our visuals once we have the correct data. We are satisfied with the scrolling parallax effect, implementation of the skeleton of the stellar evolution tree, and progress thus far. Further improvements will be to adjust color palettes, fonts, and transitions of the interactive features.