Visualization of Multiple Star Evolution

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Abstract

This paper describes a means of visualizing the various stages of stellar evolution in a real-time and customizable fashion. It first explains stellar evolution theory to the extent that it is utilized in the simulations. It then explains how various aspects of stellar evolution are incorporated into the simulations and how they are visualized.

1. Purpose

The purpose of the digital demo room (DDR) is to visualize the abstract concepts of stellar evolution to enhance student learning of the subject. Many different factors affect the evolution of a star. Properties like the evolving effective surface temperature and luminosity can be studied in a purely mathematical way, but real insight can be gained by plotting their surface temperature versus luminosity on a Hertzsprung-Russell (HR) diagram. A static HR diagram, such as those found in textbooks, can give a snapshot of stellar evolution. Here, we have developed an animated HR diagram that accepts a wide variety of possible inputs and can display one or many stars' real-time evolution in a number of styles. Depending on the prior knowledge of the user, the simulation can be tailored to show beginning material (e.g. evolution tracks), complicated material (e.g. metallicity's effect on temperature), or a wide variety of minor effects that texts usually do not cover. Any user requested simulation will typically be created and available for viewing or download within two minutes. We also have an archive of simulation movies demonstrating specific features and interesting science available for immediate download. The intended users of DDR are classrooms, either a professor during lecture, or students in a lab using the site individually. The core of our simulation is a professional scientific code for approximating stellar evolution, giving students and teachers access to an advanced level of simulation accuracy usually not available to them.

2. Overview of Stellar Evolution

2.1 Hertzsprung-Russell Diagrams

An HR Diagram is a plot of the luminosities of stars versus their effective surface temperatures, both plotted as base 10 logarithms. The reason HR Diagrams are traditionally logarithmic is that as a star evolves, its luminosity and effective surface temperature can change by many orders of magnitude. Effective surface temperature is the temperature that a blackbody would be at while emitting the same peak radiation that the we see from the star. This should be fairly close to the actual surface temperature, but other temperatures not on the surface of the star will be quite different. Note that from this point on, we will refer to the effective surface temperature as simply temperature unless otherwise mentioned. It is also traditional to plot the temperature increasing to the left and luminosity as increasing upwards on HR diagrams. Therefore, stars in the upper left part of the diagram will have the highest temperatures and highest luminosities.

2.2 Main Sequence

Our simulation begins with stars plotted on the main sequence. On the HR diagram, the main sequence is an almost straight line from the upper left to the lower right region of the diagram. We do not concern ourselves with showing any of the very short-lived protostellar evolution. In our simulations, stars begin on the main sequence where they spend most of their lives. It is at this time in a star's life that it is in hydrostatic equilibrium and is turning hydrogen into helium and energy in its core in a process known as thermonuclear fusion. The star is very stable once it reaches this point and will exist on the main sequence until the core hydrogen fusion ceases. During this stable hydrogen fusion process, a star's properties will evolve very little. A low-mass star will increase in luminosity as well as temperature as it fuses its hydrogen, causing it to move slightly up along the main sequence (to the upper left). A high-mass star will increase in luminosity but decrease in temperature, causing it to slowly move off the main sequence to the right on the HR diagram (Hurley et al. 2000). There is also a correlation between a star's mass and its initial location on the main sequence. The higher a star is on the main sequence (i.e. the higher its luminosity and temperature), the higher its mass will be.

2.3 Hertzsprung Gap or Subgiant Branch

After most of the hydrogen in a star's core has been fused to helium, fusion stops, and the now helium core begins to contract due to its self-gravity. Hydrogen fusion still continues in a thin layer above the core. The star begins to evolve off of the main sequence at this point. As the helium core contracts, the layers above the core increase in temperature due to the release of gravitational energy. This rising temperature causes the hydrogen fusion rates to increase. This increase causes the outer layers of the star to expand and cool and thus redden. At this point the star is becoming a red giant star (Chaisson and McMillan). As this occurs, the star moves to the right of the main sequence on the HR diagram. As the star leaves the main sequence, and just before it becomes a red giant, it will enter the Hertzsprung gap or subgiant branch. This occurs very rapidly, usually in less than a million years, and at an almost constant luminosity. The short timespan makes it difficult to actually observe stars in this phase of evolution (Hurley et al. 2000).

2.4 Giant and Horizontal Branches

After the star leaves the short-lived subgiant branch, it enters the giant branch as the core continues to collapse and the outer layers continue to expand. Eventually, the helium core of the star will reach a critical temperature and pressure at which the helium will begin to fuse into carbon and oxygen. For a star of mass less than about 2 solar masses, the star will have a degenerate helium core at the time of helium fusion and will begin this new fusion process rather violently in what is known as the helium flash. The helium flash can be seen on the HR diagram as a spike in the movement of the lower mass stars' evolutionary tracks. Immediately after the helium flash, a star rapidly moves down the HR diagram (towards lower luminosity) and then back towards the main sequence in a horizontal fashion (towards higher temperatures) into a period of stable helium fusion known as the horizontal branch. This transition onto the horizontal branch is more gradual for stars of mass greater than about 2 solar masses. For stars of mass greater than about 12 solar masses, it is possible for the core temperatures of these stars to rise quickly enough that helium fusion begins with almost no giant branch phase of evolution. This can be seen on the HR diagram as stars of this mass move horizontally away from the main sequence without significantly increasing luminosity (Chaisson and McMillan, Hurley et al. 2000).

2.5 Asymptotic Giant Branch and Red Supergiants

The new helium fusion process does not last very long compared to the original hydrogen fusion process that occurred on the main sequence. The higher temperature in a star's core present at the time of helium fusion causes the rate of helium burning to be higher than that of the previous hydrogen core burning (Chaisson and McMillan). The luminosity is similar to what it is on the main sequence, even though helium fusion only releases 1/10 of the energy per unit mass that hydrogen fusion does. After all of the helium has been fused in the core of a star, the star undergoes changes similar to the changes it went through after the main sequence phase. The now carbon/oxygen core begins to contract under its own gravity as the outer layers of the star again expand and cool. This phase of stellar evolution is known as the asymptotic-giant branch and can be seen on the HR diagram as the path of the star as it moves away from the horizontal branch towards a region of lower temperature and in the case of lower mass stars, higher luminosity. The star is now becoming a red supergiant (Chaisson and McMillan, Hurley et al. 2000).

2.6 Carbon/Oxygen White Dwarfs - the Fate of Medium Mass Stars

What happens next to the star depends critically on its mass. If the star's mass is less than about 8 and greater than about 0.3

solar masses, the star ends its life as a carbon/oxygen white dwarf (Hurley et al. 2000). As the carbon/oxygen core contracts, the outer layers become more and more unstable, eventually expanding off of the star completely and creating what is known as a planetary nebula. The remaining carbon/oxygen core contracts to the point at which electron degeneracy pressure counteracts the inward pull of gravity. This degeneracy pressure is not any kind of gas pressure, is independent of temperature, and only occurs at very high density ($>10^6 g/cm^3$). It is at this point that the core of the now dead star has become a white dwarf, an extremely dense star that has a high temperature but a low luminosity. The white dwarf region is at the lower left of the HR diagram, below the main sequence (Chaisson and McMillan, Hurley et al. 2000).

2.7 Helium White Dwarfs - the Fate of Low Mass Stars

A star of mass less than about 0.3 solar masses never reaches high enough central temperatures to fuse helium into carbon and oxygen. However, after a long time, the star's outer layers will dissipate into a planetary nebula because of the low gravitational pull, revealing a mainly helium core that is known as a helium white dwarf (Chaisson and McMillan).

2.8 Supernovae - the Fate of High Mass Stars

At the other extreme, a star of mass greater than about 8 solar masses will have a core too massive to be supported by electron degeneracy pressure after the carbon/oxygen core contracts. The star is massive enough that it goes through several more fusion processes (carbon and oxygen can fuse to neon, etc.). Each new fusion process gives less energy and lasts for less time, until the core has become primarily iron. As the star goes through these different fusion processes, it moves on the HR diagram somewhat horizontally away from and to the right of the main sequence. Once the core becomes iron, no fusion process can counteract the gravitational pull of the core on itself. Fusion of iron is an endothermic process, absorbing energy instead of releasing it, making it impossible for iron to be fused as an energy source for the star. Thus, the iron core collapses due to its own gravity, until the central densities reach $10^{14} g/cm^3$, near the densities of atomic nuclei. At these densities, neutron degeneracy pressure (stronger than the electron degeneracy pressure) prevents further collapse. The inner core is now a proto neutron star, and the neutron degeneracy pressure rebounds the outer material. This rebound sends a shockwave up through the rest of the star, exploding the outer layers of the core as well as the outer layers of the star itself in a violent event known as a type II supernova (Hurley et al. 2000).

2.9 Neutron Stars and Black Holes

What happens to the remaining core after this explosion depends on the remaining core's mass. If the core's mass is less than about 3 solar masses, the core's neutron degeneracy pressure continues to counteract the inward pull of gravity, stabilizing it into a neutron star. Neutron degeneracy pressure occurs at much higher densities than electron degeneracy pressure, making neutron stars even denser than white dwarfs. Neutron stars are also dimmer than white dwarfs, putting them even lower on the HR diagram, but still in the same general region below the main sequence. Many neutron stars have strong remnant magnetic fields. Some of these neutron stars collect infalling matter at and radiate out of their magnetic poles. We observe these stars as pulsars. If the core's remaining mass is greater than about 3 solar masses, not even neutron degeneracy pressure will be able to withstand the inward pull of gravity, and the core will collapse into a black hole from which no electromagnetic radiation can escape (Chaisson and McMillan).

2.10 Naked Helium Stars

Stars of mass greater than about 15 solar masses go through one additional phase of evolution. These stars lose a significant amount of their initial mass to strong stellar winds. These stars may even lose their entire outer envelope during helium fusion or sometimes during the quick subgiant phase. If this occurs, the stars' helium burning cores will be revealed before they have become white dwarfs or neutron stars, making stars known as naked helium stars. They appear to the left of the main sequence at the very highest temperatures (>50,000 K).

3. Visualization Methods

3.1 Stellar Evolution Code

The evolution of each star in this simulation is calculated with the single star evolution (SSE) code written by Dr. Jarrod Hurley et al. This code uses many analytic approximations, but it has been tested to be accurate within five percent of a more comprehensive stellar evolution code. It can calculate hundreds of star evolutionary tracks every second, which is necessary for real-time simulations such as our Digital Demo Room (DDR). This SSE program assigns each star into one of fourteen different evolution classes at each timestep (and two additional classes not used here):

1 - Main Sequence star
2 - Hertzsprung Gap
3 - First Giant Branch
4 - Core Helium Burning
5 - First Asymptotic Giant Branch
6 - Second Asymptotic Giant Branch
7 - Main Sequence Naked Helium star
8 - Hertzsprung Gap Naked Helium star
9 - Giant Branch Naked Helium star
10 - Helium White Dwarf
11 - Carbon/Oxygen White Dwarf
12 - Oxygen/Neon White Dwarf
13 - Neutron Star
14 - Black Hole

For each class, an analytic formula is known that fits data from a comprehensive stellar evolution code. This formula is a function of initial mass, metallicity, and time. Binary stars and specific kinds of mass loss are incorporated in SSE, but are not used in the DDR. The SSE formula returns current total mass, core mass, luminosity, temperature, radius, and spin at every timestep for an individual star.

3.2 Parameters

We limit the possible input masses to lie between 0.1 and 100 solar masses. Below about 0.1 solar masses, stars will probably not begin hydrogen fusion. It's uncertain if any stable stars with masses greater than 100 solar masses exist.

Metallicities are calculated as the log of the mass fraction of elements heavier than Helium(He) in the star, and the starting metallicity affects the subsequent evolution. The main sequence is based on stars of solar metallicity (0.02). For this reason stars created with different metallicities may not begin precisely on our main sequence. The metallicity ranges from 0.0001 to 0.03. Stars with extremely low metallicities are slightly warmer and appear to the left of the main sequence. Stars with high metallicities are cooler and appear to the right.

3.3 Initial Stellar Mass Function

The formation of stars in a star cluster is determined by a stellar mass function or initial mass function (IMF). This mass function is an analytic model for determining the approximate number density of a star of a particular mass in a star cluster. Basically, it is a function that describes how many stars of which masses would exist in a cluster if every star was born at the same time. (Binney and Merrifield). The stellar mass function that we use in our simulation is found in *Allen's Astrophysical Quantities: Fourth Edition,* and is known as the Scalo equations.

$$\xi(M) = \begin{cases} 0.035M^{-1.3}, \ 0.08 \leq M \leq 0.50, \\ 0.019M^{-2.2}, \ 0.50 < M \leq 1.0, \\ 0.019M^{-2.7}, \ 1.00 < M \leq 100, \end{cases}$$

This IMF describes the number of stars in a stellar population within a specific differential mass range (Allen). The number of higher mass stars in a given stellar population allowed by this IMF is much smaller than the number of lower mass stars. The result is that for star clusters and stellar populations which this IMF models, there should be many more low mass stars than high mass stars, and such is the case observationally.

In our simulation, we have given the user the option of choosing a number of randomly massed stars that will be generated by our code determined by the above IMF. In essence, the user has the ability to create a newly formed stellar population between any mass range he/she chooses, with masses accurately determined by the IMF, and to watch it evolve on an HR diagram. To utilize the IMF in creating these randomly generated masses, we first normalize the IMF to a peak value of 1. We then randomly generate a mass between the user's limits, and this random mass is input into the part of the IMF that corresponds to its mass. We then generate another random number, this time between 0 and 1, and we test this number. If this new number is greater than the value that we received from inputting the random mass into the IMF, we reject the random mass and we start over, generating a new random mass. If this new number is less than or equal to the IMF's output value, we keep the random mass and use it as one of the stars that goes to the final simulation. This happens many times until as many randomly massed stars as are needed have been accepted. Essentially, what we did was to generate a random mass, check its probability of existing in a stellar population with the normalized IMF, and then either reject it or keep it depending on this probability.

3.4 Timescales

The stable hydrogen burning lifetime of a star can vary from a few million years for high mass stars to tens of billions of years for low mass stars. We give the user a choice of 500, 1000, or 1500 frame movies. To see the details of the evolution of both high mass stars and low mass stars in the same movie would require varying the rate that time passes. This approach would give a false sense of the relative timescales; so all of the DDR movies are in linear time. To make sure the time scale for each movie encompasses the lifetimes of all stars used, the ending time is set by the lifetime of the lowest mass star in the movie. The lifetime is defined to be the point at which the star becomes a white dwarf, neutron star or black hole. The movies show an additional fifteen percent past the longest lifetime to show cooling of the final states. This way a group of very high mass stars will only be evolved for a few million years. With a lower final time, each frame is a smaller timestep, and different stages can be seen in detail. In order to better view these different stages, the user has the option for the stars to leave trails on the graph.

The default setting for the simulation creates all stars at the same time. This creates a very clear turnoff point on the main sequence, as higher mass stars rapidly evolve. Other options allow for multiple star creation times (having several 'starbursts'), or continuous star creation. Within the continous creation, there are options for having a constant, increasing, or decreasing star creation rate. This allows simulations to be tuned to specific creation environments, such as HII regions or globular clusters.

3.5 Axes

The axes of the HR diagram were chosen to highlight the evolution closest to the main sequence. The cooling of white dwarfs and neutron stars is included in the SSE code, but we felt that it was too uncertain to focus attention on. Neutron stars do not appear within the bounds of the graph. White dwarfs appear for most of their cooling phase. Black holes have no intrinsic luminosity and do not appear at all. Naked helium stars are so hot, that to expand the axes to fit them on the graph would shift the attention away from the main sequence. For that reason, naked helium stars do not appear on the graph, although their supernovas still appear near the axis labels. The very highest mass stars can also briefly become too luminous to appear within the bounds of the graph.

3.6 Colors

The colors of the stars are not exact, but instructional nonetheless. Color is determined entirely by the star's temperature, but there is no exact formula to translate temperature into an RGB triplet. Blackbody peak radiation wavelength can be used as an estimate. For this simulation, six different colors were chosen and associated with specific temperature ranges. The colors were based on the colors assigned to real stars. For stars that lie outside of those specific temperature ranges, the color is interpolated in RGB between the two nearest colors. Blue is associated with main sequence high mass stars and red is associated with main sequence low mass stars and red giants. In between these colors we have light blue, white, yellow, and orange, in order of decreasing temperature.

3.7 Radius and Spin for single stars

Since temperature and luminosity can seem rather abstract to beginning students, radius data is also incorporated into the simulation for single star movies. The radius data is reconstructed from the temperature and luminosity. The formula $R^2 \sim L/T^4$ is used to calculate the star's radius at each time. The radius of a star can range from about 0.1 to 1000 times the radius of the sun; so we show a picture of a star with a radius proportional to the log base 10 of its true radius, in the appropriate color. This is shown in a separate box next to the HR diagram. This way a student can see a star expanding and contracting through its various phases.

This same box that shows the star's size also demonstrates the star's rotation. An analytic approximation to the rotation rate of stars is used for animation purposes, and the rotation rate changes as the star evolves. However, our simulation shows the rotation of the star on a different timescale than the evolution timescale. While every frame represents at least several thousand years, a typical star will complete one revolution in a matter of days. We add the rotation to the simulation to show qualitatively that not only do stars rotate but that the rotation rate changes with radius.

Finally, an attempt is made to account for convective versus radiative surfaces. Below about 1.2 solar masses, a star's surface is convective, leading to solar flares, sun spots, and a highly unstable appearance. For high mass stars, the surface is radiative and generally thought to be quite uniform, so the picture is smoothed out. What is left after smoothing is enough to notice rotation, but not enough to indicate violent surface activity.

3.8 Star Death

When a star exhausts its fuel, it can either go supernova or create a planetary nebula. This is the most dramatic event in the star's life, so it is highlighted in the simulation. When a star first forms its planetary nebula, a small circle is drawn on the HR diagram where that star was, and a picture of a planetary nebula is shown briefly in the box to the right. Planetary nebulae for stars greater than about 2 solar masses (but not high enough to go supernova) have a round shape while those of lower mass stars have more elliptical or bipolar shapes. The pictures shown in the movie reflect this difference. When a star goes supernova in the movie, a small flare is drawn on the HR diagram where the star was, the HR diagram flashes for one frame, and a picture of a supernova remnant is briefly shown in the box to the right. Both circles and flares fade away with time, so that a movie with many stars does not become too cluttered. A minor flaw with this visualization happens when wide ranges of star masses are used. The highest mass stars will appear to go supernova on or near the main sequence in the first few frames. This is because in these particular simulations, the time elapsed between frames is on the order of the lifetimes of the high mass stars.

4. Conclusions

The Digital Demo Room Stellar Structure and Evolution Simulator uses animated Hertzsprung-Russell diagrams to provide visualization of stellar evolution. These animated diagrams are customizable through the internet, and can accommodate different levels of knowledge. Thus, the simulator provides a means for instructors to teach students about stellar evolution in a visual fashion to supplement text book learning.

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