Astronomical research: Stellar phases

Personal project

25 October 2023

Last update: 15 November 2023 Version 3.0

Saamie Vincken

Contents

Version control

Name	Version	Date	Description	Details
Saamie	0.1	20/09/2023	First setup	Initial list of phases included
Saamie	0.2	21/09/2023	Additional information phases	Explanation of each phase
Saamie	0.3	27/09/2023	Conditions for conclusion	Add conditions for inclusion for each phase
Saamie	0.4	7/10/2023	Hertzsprung-Russell diagram	Add Hertzsprung-Russell diagram and equations
Saamie	0.5	10/10/2023	Update equations	After further research update equations
Saamie	1.0	15/10/2023	Conclusion	Add conclusion
Saamie	2.0	25/10/2023	New equations	Add new equations for main sequence lifespan and newton's gravitational law
Saamie	2.1	13/11/2023	Questions	Add main and sub question to provide more meaning (feedback)
Saamie	2.2	13/11/2023	A star's lifetime introduction	Add introduction to the basics of a star's lifetime (feedback)
Saamie	2.3	14/11/2023	Comparison table stellar phases	Add comparison table for stellar phases and their relevance to this project
Saamie	2.4	14/11/2023	Rearrange document	- Rearrange chapters of document to provide a clearer flow - Add tables instead of lists for conditions for inclusion to improve overview
Saamie	2.5	15/11/2023	Correlation to project	Connecting research to project implementation: - Conditions for inclusion for each phase and sequence - Equations purpose for the algorithm (feedback)
Saamie	3.0	15/11/2023	Conclusion	Update conclusion based on research questions

Introduction

For this project, multiple calculations for finding the sequence and phase a star is in are needed. To understand and create a functional application, it is important to ensure that these calculations are fully correct.

This document is a guide for understanding the phases of stars' life cycle. It explores both main sequence phases like red dwarfs, yellow giants, and blue giants, and other phases including proto stars, red giants, supernovae, neutron stars, white dwarfs, and black holes.

The primary goal is to define inclusion criteria for identifying a star's current phase, focusing on luminosity, mass, and surface temperature. The research done will provide a basis for the implementation of astronomical calculations in algorithms needed to create properties for a 3D model.

Questions

The following questions have come up during research of the Stellar phases and sequences.

Main question

What properties and calculations are needed to define which phase a star is in?

Sub questions

1. What is a star's main sequence and how can we define it?
2. Which phases should be selected to use for this project?
3. What is a star's phase and how can we define it?
4. What equations are needed to calculate the specific properties of a star?
5. What properties need to be provided by a user to have the correct values for each equation?

What is a star's main sequence and how can we define it?

Each star has its main sequence which is the most stable and longest part of their life. How can we define if a star is in its main sequence, and what conditions should it have to be able to define it? This information is needed to implement an algorithm for categorizing main sequence stars.

Which phases should be selected to use for this project?

Additional to the main sequence, the star's lifetime can be divided up into many phases. There are so many phases that the amount causes a workload for this project which is not within its scope. Because of this a selection of a few phases should be made which are the most influential on a star's life and are good contenders for a visual representation.

What is a star's phase and how can we define it?

The goal of this sub question is to find the conditions a star has to have for it to be in a certain phase. These conditions should define clear boundaries for the transitions between phases and are needed to create an algorithm for categorizing the phases.

What equations are needed to calculate the specific properties of a star?

To define specific details of a star additionally to which phase it is in, multiple values and relations between them are needed. These values should be explored to find out which are relevant to this project and add value to the creation of a visual representation using 3D models.

What properties need to be provided by a user to have the correct values for each equation?

To use the previously defined equations, certain properties are needed. This question should answer if there are properties which need to be provided by a user, and which ones can be calculated using multiple relations between equations.

Understanding a star's lifetime

This document contains detailed information about stellar theories and equations, which is why this chapter serves as an overview on the stellar phases and sequences, providing a basis for the upcoming chapters.

A star is a very complicated object which has many properties and factors influencing its appearance. Often having a life cycle that span billions of years. The following overview can be made from its life:

Birth: Stars are born in large clouds of gas and dust called nebulae. When the gas and dust come together by the influence of gravity, a star's core is born, gradually gaining more mass.

Main sequence: When the star's core gets hot enough, nuclear fusion begins, and the star enters its "main sequence" stage. The main sequence is a very stable stage of a star's lifetime, it shines steadily for millions to billions of years by turning hydrogen into helium.

Low to medium size stars: A star's life after the main sequence depends mainly on its mass. Low to medium sized stars, like our sun, expand into red giants, growing in size and becoming cooler. After this they shrink into dwarf stars.

Massive stars: High mass stars have more influential ends. They go through phases where they expand into a supergiant and potentially explode into huge explosions caused by collapsing gravity.

Afterlife: After one of those massive explosions, massive stars might form neutron stars or black holes. Neutron stars are super dense balls of neutrons, and black holes are regions in space where gravity is incredibly strong.

Stellar values: Because values of properties in a star are so incredibly huge, the values are often defined using solar units ($\odot$). One solar unit is equal to one times our sun's value for that parameter. So for our sun, the value for solar mass is 1 Solar mass ($M_\odot$) and the value for luminosity is 1 Solar luminosity ($L_\odot$). These units are used for most of the objects in space to create a better understanding of their huge numbers.

The following figure[1] is a visual representation of the (average) lifecycle of a star:

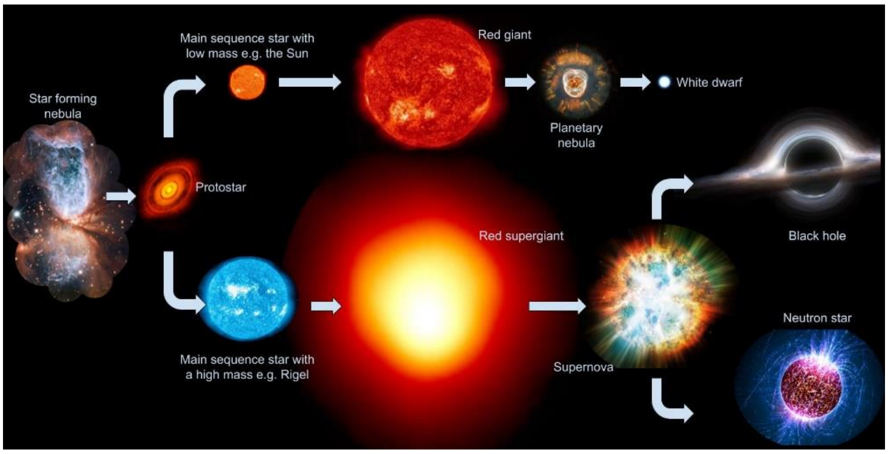


Figure 1: The life cycle of both low mass and high mass stars

[1] (Toogood, n.d.)

Overview of stellar phases

The following table provides an overview and comparison between stellar phases and which ones are relevant to this project.

Table 1: Stellar phases comparison

Features → Phases ↓	**Common Occurrence**	**Visual Appeal**	**Educational Value**	**Accessibility for Study**	**Description**
Red Dwarf	High	Moderate	High: Stellar evolution	Observable	Main sequence: small, dim, long-lived
Blue Giant	Moderate	High	High: Stellar dynamics	Observable	Main sequence: massive, hot, luminous
Red Giant	Moderate	Moderate	High: Stellar aging	Observable	Post-main sequence: large, cooler
Proto Star	High	High	Moderate: Stellar formation	Observational challenge	Early stage: gas and dust collapse
Supernova	Rare	High	High: Element creation	Observable	Explosive end: releases huge energy
Neutron Star	Rare	High	High: Matter dynamics	Observable	Post-supernova: dense, contains huge energy
Black Hole	Rare	Moderate	High: Space-time	Observable challenge	Post-supernova: gravitational singularity
White Dwarf	High	Moderate	Moderate: Stellar remnants	Observable	Post-main sequence: dense and low mass
Yellow Giant	High	Moderate	High: Evolutionary stages similar to our sun	Observable	Late stage: intermediate between giant phases
Subgiant	Moderate	Moderate	High: Stellar evolution	Observable	Transitional stage between main sequence
Hypergiant	Rare	Moderate	Low: Late-stage evolution	Observable	Rare, massive, and extremely luminous
Wolf-Rayet Star	Rare	Moderate	Moderate: Massive star evolution	Observable	Hot, luminous stars, post-main sequence
Planetary Nebula	Rare	Low	Low: Stellar remnants	Observable	Result from certain stars' late evolutionary stage
Pre-Main Sequence	Moderate	Moderate	Moderate: Star formation	Observational challenge	Early stage: stars not yet in the main sequence

Pulsating Star	Rare	Moderate	Low: Stellar dynamics	Observable challenge	Stars that vary in brightness rhythmically
R Coronae Borealis	Rare	Moderate	Low: Late-stage evolution	Observable	Unusual stars that experience sudden dimming
Brown Dwarf	Rare	Low	Low: Sub-stellar objects	Observable	Sub-stellar objects; failed stars

Sequences and phases

Because there are many different phases that depend on different variables, 10 phases have been selected that will be implemented in the 3D models in the application.

The phases are divided into different parts of a star's life: the main sequence[2] and the other phases[3]. The following phases are the ones which have been selected to use in this project.

Main sequence

- Red dwarf
- Yellow giant
- Blue giant

Other phases

- Red giant
- Proto star
- Supernova
- Neutron star
- Black hole
- White dwarf

Why have these phases been selected?

Based on the comparison table of phases (ref: *Table 1: Stellar phases comparison*), the 10 phases have been selected because of their:

Common occurrence: These phases are among the most frequent in stellar a star's life cycle.
Visual appeal: They offer distinct visual characteristics ideal for 3D representation.
Diversity: Covering birth (protostar) to the end stages (supernova, neutron star, black hole) and present a diverse range of a star's life cycle.
Educational value: Each phase holds significance for scientific research, offering insight into precise properties influencing the star and objects around it.
Accessibility for study: They are observable objects and detectable by astronomical tools, allowing for study and data collection.

[2] (Roberts, 2018)
[3] (Life Cycle of a Star)

Main sequence

The main sequence is a part of a star's life where it is really stable, balancing its gravity inward and outward. It has conditions for potential planet formation and is one of the most commonly studied parts of a star's life cycle.

Conditions for inclusion main sequence

To find stars that are in their main sequence, some values must be met for inclusion[4] :

1. Luminosity greater than 0.1 and less than 10 times the solar Luminosity (L⊙)
2. Solar mass equal or smaller than 20 times the solar Mass (M⊙)
3. Surface temperature greater than 10,000 K

These conditions can be used to write a function to categorize stars in their main sequence. Because the main sequence is the largest part of a star's life, it is important to use the correct values for the algorithm. If the conditions are not correct, it will influence the categorization of all other phases and return incorrect results in equations and visual aspects.

Main sequence phases

From the 10 chosen phases (Ref: ***Sequences and phases***), 3 phases take place during the main sequence. These 3 phases are Red dwarfs, Yellow giants and Blue giants. The following lists their conditions for inclusion which are used to write a function for categorizing main sequence stars into their phases.

Table 2: Main sequence phase conditions

Phase → Property ↓	**Red Dwarf**	**Yellow Giant**	**Blue Giant**
Mass	0.08 - 1.2 M⊙	1.2 - 2.1 M⊙	2.1 - 20 M⊙
Temperature	2,500 K - 3,500 K (approx. range)	5,000 K - 6,000 K (approx. range)	15,000 K - 30,000 K (approx. range)
Luminosity	On average 0.01 L⊙	0.1 - 10 L⊙	> 10 L⊙

Red Dwarf

Red dwarfs are the most common type of star and have relatively low mass compared to other main sequence stars. Often lasting for billions or even trillions of years due to their slow consumption of fuel. [5][6]

Yellow giant

Yellow giants are the same phase our sun is currently in. This phase is mainly known because of its stable environment for potential habitable plants.[7]

Blue Giant

Blue giants are massive, hot, and luminous stars within the main sequence. Having short lifespans compared to other stars due to their high rate of energy production and consumption.[8]

[4] (Thompson, Introduction to Stars, Galaxies, and Cosmology)
[5] (Gregersen)
[6] (Tillman N. T., Red dwarfs: The most common and longest-lived stars, 2019)
[7] (Scelsi, Maggio, & Pallavicini, 2004)
[8] (Cain, 2009)

Later stages after or before the main sequence

Other phases of a star outside of its main sequence are much more extreme and often consist of large explosions or changes in gravity.

From the 10 chosen phases (Ref: ***Sequences and phases***), 7 phases take place before or after the main sequence. These 7 phases are Proto stars, red giants, supernovae, neutron stars, white dwarfs, and black holes. The following lists their conditions for inclusion which are used to write a function for categorizing the star into it's correct phase outside of the main sequence.

Table 3: Later stages conditions for inclusion

Phase → Property ↓	**Proto Star**	**Red Giant**	**Supernovae**	**Neutron Star**	**White Dwarf**	**Black Hole**
Mass	> 0.08 M⊙ and < 1 M⊙	> 2 M⊙	> 8 M⊙	1.4 - 2.1 M⊙	< 1.4 M⊙	> 20 M⊙
Temperature	< 500 K	< 4,000 K	> 10,000 K	> 1e9 K	> 5,000 K	N/A
Luminosity	On average 0.01 L⊙	< 10 L⊙	> 100 L⊙	> 10,000 L⊙	< 10 L⊙	N/A

Proto star

A protostar is where a cloud of gas and dust begins to collapse under the influence of gravity, forming a new star.[9]

Red giant

Formed when a star runs out of hydrogen fuel in its core and becomes much larger and colder.[10]

Supernovae

When massive stars exceed a critical mass, they undergo core collapse and then explode as supernovae, releasing an enormous amount of energy.[11] [12]

Neutron star

When a massive star undergoes a supernova, the core collapses, and if the remaining mass falls within the Chandrasekhar limit[13], it forms a neutron star.[14]

White Dwarf

A white dwarf is the remnant of a low to medium-mass star (like the Sun) after it has exhausted its nuclear fuel and shed its outer layers. [15] [16]

Black Hole

A region of spacetime where gravity is so strong that nothing, not even light, can escape. Formed from the remnants of massive stars after a supernova explosion or through other processes. [17] [18] [19]

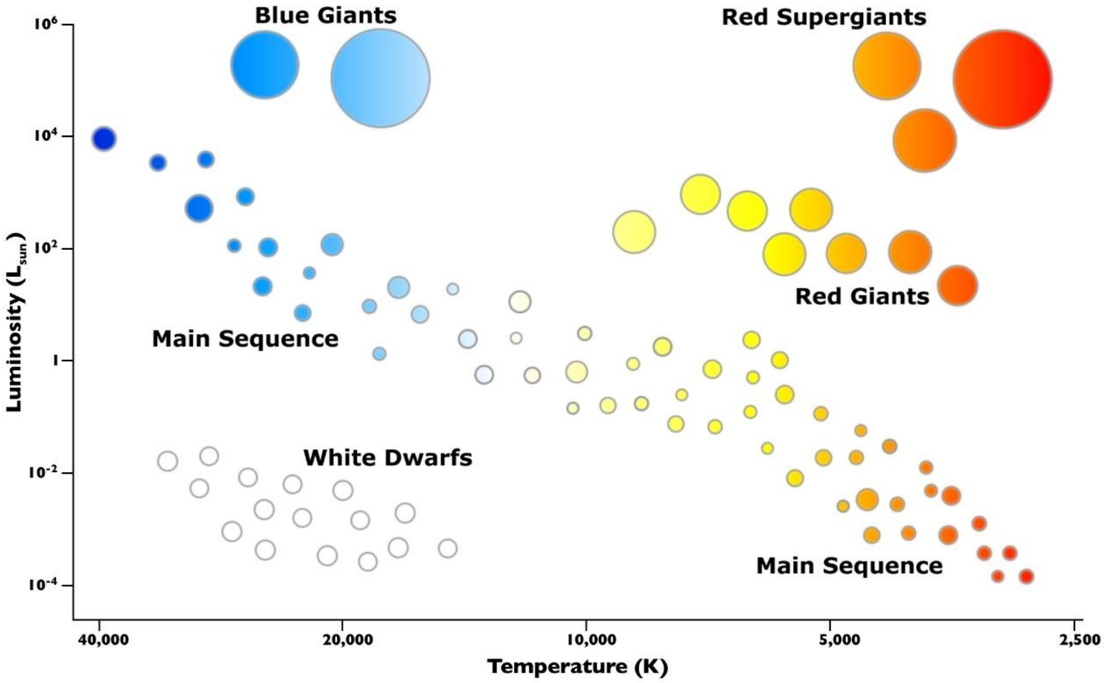
---

[9] (Las Cumbres Observatory)
[10] (Tillman N. T., Red giant stars: Facts, definition & the future of the sun, 2023)
[11] (Kohler, 2016)
[12] (Radboud university, Pre-supernova evolution of massive stars)
[13] (Lea, 2022)
[14] (Miller)
[15] (Osada, Capelato, & Bilha)
[16] (ESA & Hubble, Whitedwarf)
[17] (NASA, Types of black holes)
[18] (Tillman & Dobrijevic, 2023)
[19] (Radboud university, The image of a black hole)

Hertzsprung-Russell (HR) diagram

The Hertzsprung-Russell (HR) diagram[20] is a graphical representation used in astronomy to classify stars based on their luminosity (brightness) and surface temperature relationship[21]. It's a scatter plot with luminosity on the vertical axis and temperature on the horizontal axis.

For main sequence stars, the HR diagram is particularly useful because the phases can be defined by a relationship between luminosity and temperature.



Star Classification: The HR diagram allows astronomers to categorize stars into different phases including the main sequence, giants, white dwarfs, and more. By plotting a star's luminosity and temperature, you can determine where it falls on the HR diagram and find the correct phase.

Main Sequence: The diagonal band on the diagram represents stars in the main sequence. Stars spend the majority of their lifetimes on the main sequence, and their position on this band is mainly determined by their mass. More massive stars are hotter and brighter and, therefore, located at the upper left part of the main sequence.

Evolutionary Path: As stars age and exhaust their hydrogen fuel, they follow different paths on the HR diagram. For instance, once a star leaves the main sequence, it may become a giant or supergiant, depending on its mass. This transition is also clearly visible on the HR diagram.

Stellar Properties: The HR diagram provides insights into various stellar properties, such as mass, radius, and age. By analysing a star's position on the diagram, these characteristics can be calculated.

Continual Refinement: The HR diagram continues to be updated with more accurate data. This allows for even more precise classifications and understanding of stars.

[20] (Mason, 2016)
[21] (Wang & Zhong, 2018)

Equations

The Hertzsprung-Russell has proved to be a very useful tool which resulted in many equations related to stellar phases[22] [23]. The following are some which will be needed for this project, many of the properties result in visual properties in a star which will then be used to create 3D models of them:

Effective temperature (Teff)

The Stefan-Boltzmann law relates the star's luminosity, radius, and effective temperature[24]:

Equation 1: Effective temperature

$$T_e = \left(\frac{L}{4piR^2\sigma}\right)^{\frac{1}{4}}$$

Where *Te* is the effective temperature in Kelvin(K), *L* is the star's total luminosity in solar Luminosity(L⊙), *R* is the star's radius in m(m), σ is the Stefan-Boltzmann constant*.

For the creation of the 3D models, this equation is used to get the surface temperature and luminosity input by a user, calculate the radius (ref:

Stellar radius), and then the effective temperature. The effective temperature is used in Wien's displacement law (ref: ***Color spectrum research****),* which calculates the wavelength of a star resulting in a color spectrum used for creating an HSL color model. This model is used to calculate the star's color based on the user's input.

** Stefan-Boltzmann constant = 5.67 x 10^{-8} W/m²·K⁴*

Stellar Density

The density of a star can be calculated using the following equation[25]:

Equation 2: Stellar density

$$\rho = M/V$$

Where ρ is the mean density* of the star in grams per cubic centimetres(g/cm³), *M* is its mass in grams(g), and *V* its volume in cubic meters (cm³).

For the creation of the 3D models, the density equation is used to get the mass input by a user, calculate the volume (ref: ***Stellar Volume***), and then the mean density.
This density value of a star is used to calculate the opacity for the visualization of a star, using Three.JS (ref: ***Technologies research***), transparency properties for creation of a 3D model.

* Mean density: *specifically used in the context of celestial bodies like planets, stars, or celestial objects.*

---

[22] (Zaninetti, 2008)
[23] (Turun)
[24] (Swinburne centre Astrophysics and Supercomputing)
[25] (Thompson, Lecture 10: The Internal Structure of Stars, n.d.)

Stellar Volume

The volume of a star can be calculated using the following equation:

Equation 3: Stellar volume

$$V = \left(\frac{4}{3}\right)\pi\, R^3$$

Where V is the volume of a star in cubic meters (m^3) and R is the radius in meters (m).

The volume of a star is needed for calculating the density (ref: ***Stellar Density***) value of a star, needed for calculating opacity values for the 3D models.

Stellar Luminosity

The luminosity or mass of a star can be estimated using the luminosity-mass relation in the following equation[26]:

Equation 4: Stellar luminosity-mass relation

$$L \approx M^{3.5}$$

Where M is the mass of the star in solar masses (M⊙) and L is its luminosity in solar luminosity (L⊙).

This equation can be used to calculate the missing input properties when a user might not have both the luminosity and mass properties of a star, but only one of them. The purpose of this is offering a more flexible user input experience by not requiring input in all fields.

Stellar radius

The formula for calculating the radius of a star (Stephan Boltzmann law[27]) using its surface temperature is[28]:

Equation 5: Stellar radius

$$R = \sqrt{\frac{L}{4\pi\sigma {T_s}^4}}$$

Where R is the radius of the star in meters(m), L is its luminosity in solar luminosity (L⊙), Ts is its surface temperature in Kelvin, and σ is the Stefan-Boltzmann constant*.

The radius is one of the important parameters needed when calculating the volume of a star (ref: ***Stellar Volume)***

In Three.js, the 3D modeling library used for this project (ref: ***Technologies research)*** the radius is used to create different geometries for objects. For stars, a sphere geometry is used since stars are typically spherical in shape. The sphere is created using a `SphereGeometry` class, with the radius as a parameter derived from the star's data. However, it is important to convert the actual radius of the star into a suitable scale for the visualization.

** Stefan-Boltzmann constant = 5.67 x 10^{-8} W/$m^2 \cdot K^4$*

---

[26] (Pennstate college, n.d.)
[27] (Impey, n.d.)
[28] (Deziel, 2020)

Optional use equations

The last two equations are within the current scope of the project not necessarily needed but do provide valuable features for future implementation.

Main sequence duration

The duration of the main sequence of a star's life can be calculated using the following equation[29]:

Equation 6: Main sequence lifetime

$$t_{MS} = 10^{10}\left(\frac{M}{M\odot}\right)^{-2.5}$$

Where *tms* is the lifespan of the main sequence in years, *M* is the mass in solar masses(M⊙) and M⊙ is the solar mass constant*.

The main sequence duration property is used to calculate the age of a star, which will be further researched in the future before implementation in the algorithm. It is needed to define exact transitions and definitions of the stellar phases. This will result in even more accurate visual representation because the specific properties of the star change based on its age.

* M⊙ ≈ 1.989 x 10^30 kilograms

Newtons law of universal gravitation

The surface gravity of a star can be calculated using its mass and radius in Newton's law of universal gravitation[30]:

Equation 7: Newtons law of universal gravitation

$$g = G * M/R^2$$

Where *g* is the surface gravity of the star in meters per second squared (m/s^2), *G* is the gravitational constant*, *M* is its mass in kilograms(kg), and *R* is its radius in meters(m).

The surface gravity can be used to calculate the pull between objects and the influence of that on its visual properties. However, this equation is within the current scope of the project not necessarily needed because the 3D model will be a singular object instead of multiple.

* Gravitational constant = 6,67384·10-11 Nm2kg-2

[29] (Swinburne University of Technology, n.d.)
[30] (Gravitatiewet, n.d.)

Conclusion

The main question regarding this documents research was as follows:

"What properties and calculations are needed to define which phase a star is in?"

The goal was to create insight into information needed to define stellar phases. This information is used to write an algorithm to take user input and create a 3D model based on the input.

The following sub questions have been addressed:

What is a star's main sequence and how can we define it?
The main sequence represents a stable phase in a star's life where it balances gravity and fusion reactions. Conditions for inclusion needed for the algorithm involve specific ranges of luminosity, mass, and surface temperature (ref: ***Main sequence***).

Which phases should be selected for this project?
Ten phases were chosen based on common occurrence, visual appeal, diversity, educational value, and accessibility for study. This selection covers the main sequence (Red Dwarf, Yellow Giant, Blue Giant) and other phases like Proto Star, Red Giant, Supernova and more (ref: ***Sequences and phases***).

What is a star's phase and how can we define it?
Each phase is defined by distinct conditions related to mass, temperature, and luminosity, providing clear boundaries between transitions between phases and the categorization of stars. These conditions for inclusions can be used to implement a function for categorizing stars into one of the 10 phases (ref: ***Sequences and phases***).

What equations are needed to calculate the specific properties of a star?
Essential equations include those determining effective temperature, stellar density, volume, luminosity-mass relation, stellar radius, main sequence duration, and Newton's law of universal gravitation. Many of these equations have been derived based on relationships in the Hertzsprung Russel diagram(ref: ***Hertzsprung-Russell (HR) diagram***). These equations can be used for calculating properties necessary for visual representation in the 3D models.

What properties need to be provided by a user to have the correct values for each equation?
Almost all equations needed for this project have relationships between them, this means only a few input values are needed from the user. Based on this research only the Temperature and either Luminosity or Mass are needed from a user to calculate all needed properties for the 3D models and all it's visual components. Every other property can be calculated using combinations of all mentioned equations in this document (ref: ***Equations***).

In summary, this document describes the criteria, equations, and phases needed for the project's implementation of an algorithm that defines the properties and uses them to create a 3D model for each phase.

Bibliography

Cain, F. (2009, February 3). *Blue giant star.* Retrieved from universetoday.com: https://www.universetoday.com/24587/blue-giant-star/

Deziel, C. (2020, December 22). *How to calculate stellar radii.* Retrieved from sciencing.com: https://sciencing.com/calculate-stellar-radii-7496312.html

ESA. (n.d.). *Red giant*. Retrieved from esahubble.org: https://esahubble.org/wordbank/red-giant/

ESA, & Hubble. (n.d.). *Whitedwarf.* Retrieved from esahubble.org: https://esahubble.org/wordbank/white-dwarf/

Gravitatiewet. (n.d.). Retrieved from Natuurkundeuitgelegd.nl: https://natuurkundeuitgelegd.nl/videolessen.php?video=gravitatiewet

Gregersen, E. (n.d.). *Red dwarf star.* Retrieved from britannica.com: https://www.britannica.com/science/red-dwarf-star

Harvard. (n.d.). *Stellar Structure and Evolution.* Retrieved from cfa.hardvard.edu: https://www.cfa.harvard.edu/research/topic/stellar-structure-and-evolution

Impey, C. (n.d.). *Stefan-Boltzmann Law*. Retrieved from teachastronomy.com: https://www.teachastronomy.com/textbook/Properties-of-Stars/Stefan-Boltzmann-Law/

IOWA. (n.d.). *Stars.* Retrieved from physics.uiowa.edu: https://homepage.physics.uiowa.edu/~pkaaret/s09/L12_starsmainseq.pdf

Kohler, S. (2016, April 8). *How bright can Supernovae get?* Retrieved from aasnova.org: https://aasnova.org/2016/04/08/how-bright-can-supernovae-get/

Las Cumbres Observatory. (n.d.). *Protostar.* Retrieved from lco.global: https://lco.global/spacebook/stars/protostar/

Lea, R. (2022, 5 12). *The Chandrasekhar limit: Why only some stars become supernovas*. Retrieved from space.com: https://www.space.com/chandrasekhar-limit

Life Cycle of a Star. (n.d.). Retrieved from byjus.com: https://byjus.com/physics/life-cycle-of-stars/

Mason, S. (2016, June 15). *What is the Hertzsprung-Russell diagram and why is it so important to astronomy research?* . Retrieved from socratic.org: https://socratic.org/questions/what-is-the-hertzsprung-russell-diagram-and-why-is-it-so-important-to-astronomy-

Miller, M. C. (n.d.). *Introduction to neutron stars.* Retrieved from astro.umd.edu: https://www.astro.umd.edu/~miller/nstar.html

NASA. (n.d.). *Neutron stars.* Retrieved from imagine.gsfc.nasa.gov: https://imagine.gsfc.nasa.gov/science/objects/neutron_stars1.html

Nasa. (n.d.). *Stars.* Retrieved from science.nasa.gov: https://science.nasa.gov/astrophysics/focus-areas/how-do-stars-form-and-evolve

NASA. (n.d.). *Types of black holes.* Retrieved from universe.nasa.gov: https://universe.nasa.gov/black-holes/types/

Osada, J., Capelato, V., & Bilha, J. (n.d.). *Mass-Luminosity Relation for White dwarf stars.* Retrieved from sbfisica.org.br: https://www.sbfisica.org.br/bjp/download/v01/v01a09.pdf

Pennstate college. (n.d.). *The Mass-Luminosity Relationship*. Retrieved from e-education.psu.edu: https://www.e-education.psu.edu/astro801/content/l7_p3.html

Radboud university. (n.d.). *Pre-supernova evolution of massive stars.* Retrieved from astro.ru.nl: https://www.astro.ru.nl/~onnop/education/stev_utrecht_notes/chapter12-13.pdf

Radboud university. (n.d.). *The image of a black hole.* Retrieved from ru.nl: https://www.ru.nl/astrophysics/black-hole/black-holes/what-does-black-hole-look-like/

Roberts, B. (2018, April 16). *7 Main Stages of a Star.* Retrieved from sciencing.com: https://sciencing.com/what-are-the-final-stages-in-the-life-of-a-star-similar-in-size-to-the-sun-12730976.html

Scelsi, L., Maggio, A., & Pallavicini, R. (2004, November 6). *Coronal properties of G-type stars in different evolutionary phases.* Retrieved from aanda.org: https://www.aanda.org/articles/aa/pdf/2005/11/aa1739.pdf

Swinburne centre Astrophysics and Supercomputing. (n.d.). *Effective temperature.* Retrieved from astronomy.swin.edu.au: https://astronomy.swin.edu.au/cosmos/e/Effective+Temperature

Swinburne University of Technology. (n.d.). *Main Sequence Lifetime*. Retrieved from astronomy.swin.edu.au: https://astronomy.swin.edu.au/cosmos/M/Main+Sequence+Lifetime

Thompson, T. (n.d.). *Introduction to Stars, Galaxies, and Cosmology.* Retrieved from astronomy.ohio-state.edu: https://www.astronomy.ohio-state.edu/thompson.1847/1144/Lecture10.html

Thompson, T. (n.d.). *Lecture 10: The Internal Structure of Stars*. Retrieved from astronomy.ohio-state.edu: https://www.astronomy.ohio-state.edu/thompson.1847/1144/Lecture10.html

Tillman, N. T. (2019, June 6). *Red dwarfs: The most common and longest-lived stars.* Retrieved from space.com: https://www.space.com/23772-red-dwarf-stars.html

Tillman, N. T. (2023, 6 29). *Red giant stars: Facts, definition & the future of the sun*. Retrieved from space.com: https://www.space.com/22471-red-giant-stars.html

Tillman, N., & Dobrijevic, D. (2023, may 19). *Black holes: Everything you need to know.* Retrieved from space.com: https://www.space.com/15421-black-holes-facts-formation-discovery-sdcmp.html

Toogood, O. (n.d.). *Life cycle of stars*. Retrieved from alevelphysicsnotes.com: http://alevelphysicsnotes.com/astrophysics/deadstars.php

Turun, U. o. (n.d.). *Modeling stars.* Retrieved from astro.utu.fi: https://www.astro.utu.fi/~cflynn/Stars/l3.html

university, W. W. (n.d.). *Hertzsprung Russell diagram*. Retrieved from wwu.edu: https://www.wwu.edu/astro101/a101_hrdiagram.shtml

Wang, J., & Zhong, Z. (2018, September 27). *Revisiting the mass-luminosity relation with an effective temperature modifier.* Retrieved from aanda.org: https://www.aanda.org/articles/aa/full_html/2018/11/aa34109-18/aa34109-18.html

Zaninetti, L. (2008, November 27). *Semi-analytical formulas for the.* Retrieved from arxiv.org: https://arxiv.org/pdf/0811.4524.pdf

Color spectrum research

The following document contains research done into the color spectrum of stars and Wien's displacement law: GitHub- Astronomical research Color spectrum

Technologies research

The following document contains research in the needed technologies for this project: GitHub- Technologies research V3