Astronomical research: Stellar phases

Personal project

25/10/2023

Saamie Vincken

Contents

Version control 2
Introduction 3
Sequences 4
Main sequence 5
Conditions for inclusion main sequence 5
Red Dwarf 5
Conditions for inclusion 5
G-Type 5
Conditions for inclusion 5
Blue Giant 5
Conditions for inclusion 5
Other phases 6
Proto Star 6
Conditions for inclusion 6
Red giant stars 6
Conditions for inclusion 6
Supernovae 6
Conditions for inclusion 6
Neutron star 7
Condition for inclusion 7
White Dwarf 7
Conditions for inclusion 7
Black Hole 7
Conditions for inclusion 7
Hertzsprung-Russell (HR) diagram 8
Equations 9
Conclusion 11
Bibliography 12

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

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, G-type, 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.

Sequences

Because there are many different phases that depend on different variables, I have selected 10 phases that will be implemented in the 3D models. These 10 phases are the most common[1][2] and have possibilities for visual representation.

The phases are divided into different sequences, the main sequence[3] and the sequence with the other phases[4].

Main sequence

- Red dwarf
- G-Type
- Blue giant

Other phases

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

To find the correct sequence, parameters solar mass, luminosity and temperature are needed. The specific values for inclusion regarding each phase will be discussed in further parts of this document.

The following figure[5] is a visual representation of the (average) lifecycle of a star:

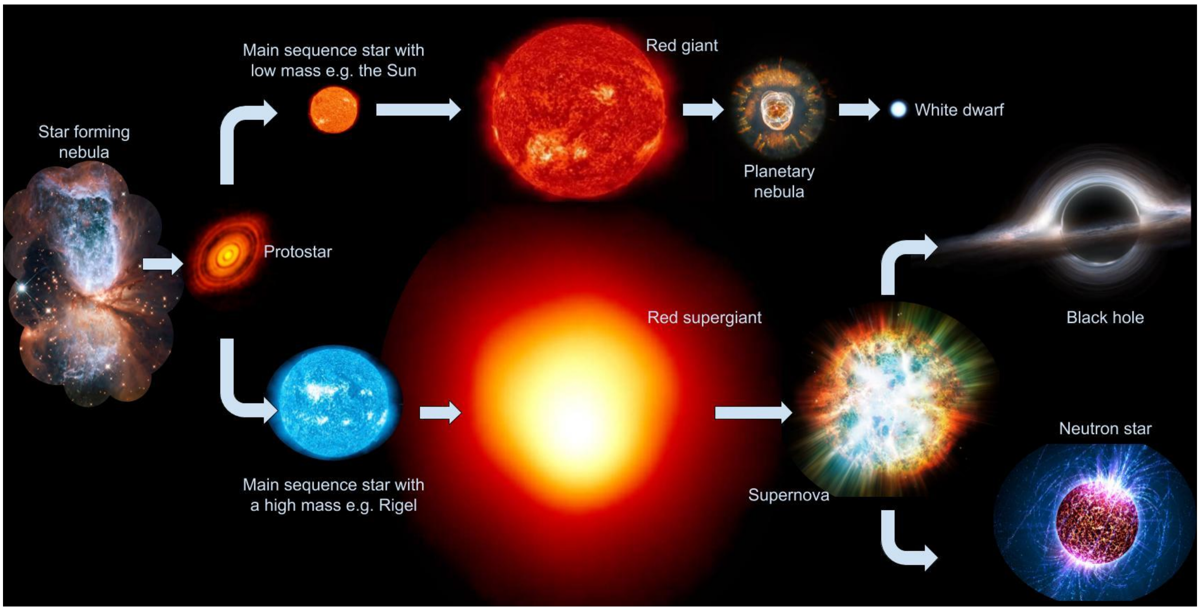


Figure 1: The life cycle of both low mass and high mass stars

[1] (Harvard)
[2] (Nasa)
[3] (Roberts, 2018)
[4] (Life Cycle of a Star)
[5] (Toogood, n.d.)

Main sequence

A difference can be made between the main sequence and the other phases. The main sequence is a part of a star's life where it is really stable, balancing its gravity inward and outward.

Conditions for inclusion main sequence

To find stars that are in their main sequence, some values must be met for inclusion[6] :

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

For this project, a selection of 3 phases has been made that represent the most important parts of a stars life in the main sequence.

Red Dwarf

Red dwarfs are the most common type of star and have relatively low mass compared to other main sequence stars. [7][8]

Conditions for inclusion

- Mass: Solar mass between 0.08 and 1.2 times the solar mass (approximate range)
- Temperature: Surface temperature between 2,500 K and 3,500 K (approximate range)
- Luminosity: On average 0.01 times the solar luminosity
- Low-mass star (<0,5 M⊙) main sequence lifetime

G-Type

G-type is the same phase our sun is currently in. This phase is mainly known because of its stable environment for potential habitable plants.[9]

Conditions for inclusion

- Mass: Solar mass between 1.2 and 2.1 times the solar mass (approximate range)
- Temperature: Surface temperature between 5,000 K and 6,000 K (approximate range)
- Luminosity: Between 0.1 and 10 times the solar luminosity
- Solar-mass star (+- 1 M⊙) main sequence lifetime

Blue Giant

Blue giants are massive, hot, and luminous stars within the main sequence.[10]

Conditions for inclusion

- Solar mass between 2.1 and 20 times the solar mass (approximate range)
- Surface temperature between 15,000 K and 30,000 K (approximate range)
- Luminosity on average greater than 10 times the solar luminosity
- Intermediate-mass star (>1 & <8) main sequence lifetime

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

Other phases

Besides the main sequence phases, this project will be incorporating 7 other phases mentioned below.

Proto Star

A protostar is an early stage in the formation of a star, where a cloud of gas and dust begins to collapse under the influence of gravity. As the core continues to collapse, it heats up and begins to emit infrared radiation. The protostar is surrounded by a disk of gas and dust that may eventually form planets.[11]

Conditions for inclusion

- Luminosity is on average 0.01 times the sun's luminosity
- Solar mass is above 0.08 (lower is a brown dwarf) and less than 1 solarMass.
- Temperature is on average lower than 500 Kelvin

Red giant stars

Red giants are formed when a star runs out of hydrogen fuel in its core and begins to fuse helium into heavier elements. This causes the outer layers of the star to expand and cool, making it appear red. They are much larger than main sequence stars but have lower surface temperatures.[12] [13]

Conditions for inclusion

- Luminosity less than 10 times the sun's luminosity
- Solar mass more than 2 times the solar mass
- Surface temperature less than 4,000 Kelvin

Supernovae

When massive stars exceed a critical mass, they undergo core collapse and then explode as supernovae, releasing an enormous amount of energy. Supernovae are some of the most energetic events in the universe. The resulting explosion releases an enormous amount of energy, outshining entire galaxies.[14] [15]

Conditions for inclusion

- Luminosity greater than 100 times the sun's luminosity
- Solar mass greater than 8 times the solar mass
- Surface temperature greater than 10,000 Kelvin

[11] (Las Cumbres Observatory)
[12] (ESA, Red giant, n.d.)
[13] (Tillman N. T., Red giant stars: Facts, definition & the future of the sun, 2023)
[14] (Kohler, 2016)
[15] (Radboud university, Pre-supernova evolution of massive stars)

Neutron star

When a massive star undergoes a supernova, the core collapses, and if the remaining mass falls within the Chandrasekhar limit, it forms a neutron star. The neutron star is a ball of neutrons with a radius of only about 10 kilometers. Neutron stars are very hot and emit intense radiation.[16] [17]

Condition for inclusion

- Luminosity greater than 10.000 times the sun's luminosity
- Solar mass between 1.4 and 2.1 times the solar mass (Chandrasekhar limit [18])
- Surface temperature greater than 1e9 Kelvin

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. They are incredibly dense, with masses similar to that of the Sun but radii only about as large as Earth's. [19] [20]

Conditions for inclusion

- Luminosity smaller than 10 times the sun's luminosity
- Solar mass less than 1.4 times the solar mass
- Surface temperature greater than 5000 K

Black Hole

A black hole is a region of spacetime where gravity is so strong that nothing, not even light, can escape from it. They are formed from the remnants of massive stars after a supernova explosion or through other processes. [21] [22] [23]

Conditions for inclusion

- Mass is at least greater than around 20 solar masses.
- Luminosity is not applicable as black holes do not emit visible light.
- No surface temperature as black holes are regions with no solid surface.

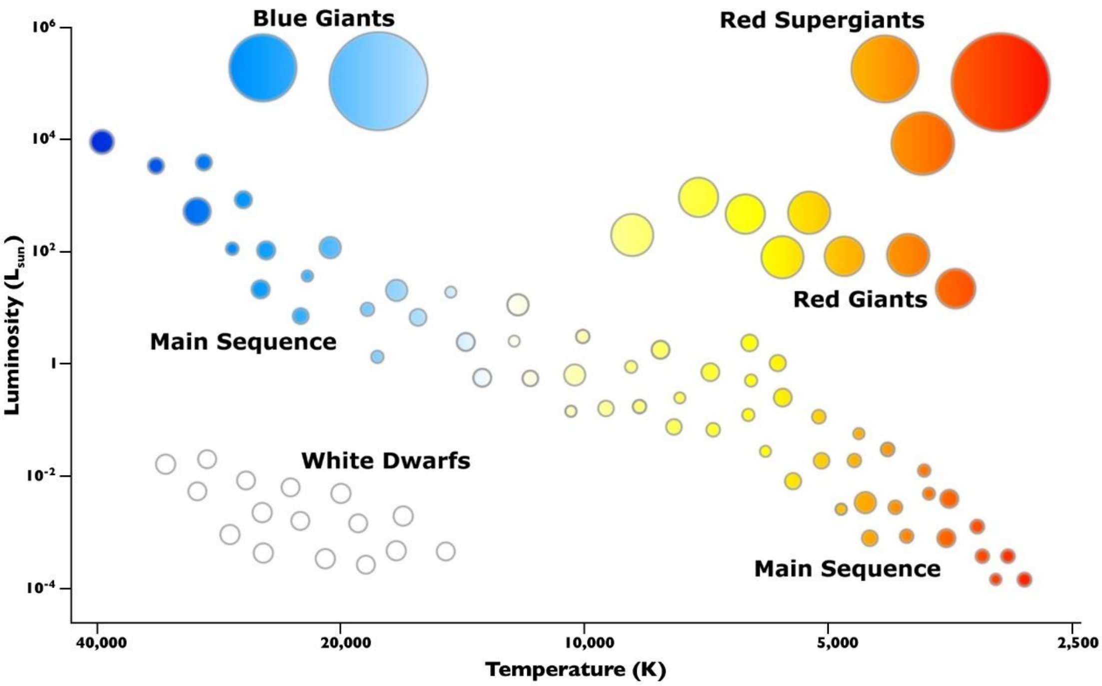
---

[16] (NASA, Neutron stars)
[17] (Miller)
[18] (Lea, 2022)
[19] (Osada, Capelato, & Bilha)
[20] (ESA & Hubble, Whitedwarf)
[21] (NASA, Types of black holes)
[22] (Tillman & Dobrijevic, 2023)
[23] (Radboud university, The image of a black hole)

Hertzsprung-Russell (HR) diagram

The Hertzsprung-Russell (HR) diagram[24] is a graphical representation used in astronomy to classify stars based on their luminosity (brightness) and surface temperature relationship[25]. 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.

[24] (Mason, 2016)
[25] (Wang & Zhong, 2018)

Equations

The Hertzsprung-Russell has proved to be a very useful tool which resulted in many equations related to stellar phases[26]. The following are some which will be needed for this project[27]:

1. Effective temperature (T_{eff})

The Stefan-Boltzmann law relates the star's luminosity, radius, and effective temperature[28]:

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 meters(m), σ is the Stefan-Boltzmann constant*.

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

2. Stellar Mass

The mass of a star can be estimated using the luminosity/mass relation in the following equation[29]:

Equation 2: Stellar Mass

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

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

3. Stellar Density

The density of a star can be calculated using the following equation[30]:

Equation 3: Stellar density

$$\rho = M/V$$

Where ρ is the mean density* of the star in grams per cubic centimetres(g/cm^3), *M* is its mass in grams(g), and *V* its volume in cubic meters (cm^3).

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

4. Stellar Volume

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

Equation 4: 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).

---

[26] (Zaninetti, 2008)
[27] (Turun)
[28] (Swinburne centre Astrophysics and Supercomputing)
[29] (Pennstate college, n.d.)
[30] (Thompson, Lecture 10: The Internal Structure of Stars, n.d.)

5. Stellar radius

The formula for calculating the radius of a star (Stephan Boltzmann law[31]) using its surface temperature is[32]:

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*.

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

6. Main sequence duration

The duration of the main sequence of a star's life can be calculated using the following equation[33]:

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*.

* M⊙ ≈ 1.989 x 10^30 kilograms

7. 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[34]:

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).

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

[31] (Impey, n.d.)
[32] (Deziel, 2020)
[33] (Swinburne University of Technology, n.d.)
[34] (Gravitatiewet, n.d.)

Conclusion

In this document all equations required to understand stellar evolution on a “basic” level are researched. Beginning with exploring the stellar phases, including those within the main sequence such as red dwarfs, G-type, and blue giant stars, as well as the other phases like proto stars, red giants, supernovae, neutron stars, white dwarfs, and black holes.

For each phase the conditions for inclusion are defined as criteria for identifying in which phase a star is in, focusing on parameters like luminosity, mass, and surface temperature. These criteria can be used for implementation of the algorithm for this project.

The Hertzsprung-Russell (HR) diagram showed to be an important tool for many equations. These equations define values like stellar mass, effective temperature, radius and density. These values contribute to the understanding of a star’s evolution and how to visualize the phases for the 3D models which will be created in the future.

In summary, this document describes the criteria, equations, and phases needed for the project’s implementation 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