Research, Society and Development, v. 9, n. 9, e993998042, 2020
(CC BY 4.0) | ISSN 2525-3409 | DOI: http://dx.doi.org/10.33448/rsd-v9i9.8042

Stellar evolution concepts and the dissemination of knowledge in Astronomy

Conceitos da evolução estelar e a disseminação do conhecimento em Astronomia

Conceptos de evolución estelar y difusión del conocimiento en Astronomía

Received: 08/31/2020 | Reviewed: 09/11/2020 | Accept: 09/14/2020 | Published: 09/15/2020

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Abstract

In this work, an information booklet on the topic of Stellar Evolution was prepared, based on a bibliographic review of the literature in the field, aiming to create subsidies for the development of this science at different levels of knowledge. The booklet, which is intended to be used by teachers and students of Basic Education, was designed as a way of contributing to the shortage of teaching materials in this field. Here, it is presented the main scientific concepts worked on the booklet to support teachers and students, as well as comments on the experience with the presentations of lectures and workshops based on the booklet, in educational environments, in the Brazilian city of Marabá, in the state of Pará, as a way of disseminating and encouraging Astronomy in the region. It was noticed that the school community, in general, has a great interest in the learning of Astronomy, which contrasts with the scarcity of didactic materials and knowledge opportunities in the field. It is expected that more proposals for teaching materials, as well as applications of activities in Astronomy, will be developed, in order to disseminate such science in the school environment, and also in the general community.

Keywords: Stellar Evolution; Star; H-R Diagram and Nuclear Fusion; Astronomy Teaching.

Resumo

Neste trabalho foi elaborada uma cartilha informativa acerca da temática Evolução Estelar, a partir da revisão bibliográfica da literatura na área, com intuito de criar subsídios para o desenvolvimento desta ciência nos diferentes níveis de conhecimento. A cartilha, que é voltada para ser utilizada por professores e alunos da Educação Básica, foi idealizada como forma de contribuição à escassez de materiais didáticos na área. Aqui são apresentados os principais conceitos científicos trabalhados na cartilha, para servir de apoio a professores e alunos, bem como é comentada a experiência realizada com a aplicação de palestras e oficinas embasadas na cartilha, em ambientes educativos, na cidade brasileira de Marabá, no estado do Pará como forma da disseminação e incentivo à Astronomia, na região. Percebeu-se que a comunidade escolar, em geral, tem grande interesse na aprendizagem da Astronomia, o que contrasta com a escassez de materiais didáticos e oportunidades de conhecimento da área. Espera-se que mais propostas de materiais didáticos, e também de aplicações de atividades em

Astronomia sejam desenvolvidas, de modo a disseminar tal ciência no ambiente escolar, e também na comunidade geral.
Palavras-chave: Evolução Estelar; Estrela; Diagrama H-R e Fusão Nuclear; Ensino de Astronomia.

Resumen

En este trabajo se elaboró un cuadernillo informativo sobre el tema Evolución Estelar a partir de la revisión bibliográfica de la literatura del área con el objetivo de crear subsidios para el desarrollo de esta ciencia en diferentes niveles de conocimiento. El cuadernillo, que está destinado a ser utilizado por profesores y estudiantes de Enseñanza Básica, fue diseñado como una forma de contribuir a la escasez de materiales didácticos en este tema. Aquí se presentan los principales conceptos científicos que son trabajados en el cuadernillo informativo, con el fin de proporcionar apoyo a los profesores y estudiantes, así como también se describe la experiencia llevada a cabo con las presentaciones de charlas y los talleres basados en el cuadernillo, en ambientes educativos, en la ciudad brasileña de Marabá, en el Estado do Pará cómo una forma de difusión e incentivo a la Astronomía, en la región. Se percibió que la comunidad escolar, en general, tiene gran interés en el aprendizaje de la Astronomía, lo que contrasta con la escasez de materiales didácticos y oportunidades de conocimiento en el área. Se espera que más propuestas de materiales didácticos y también de aplicaciones de actividades en la Astronomía sean desarrolladas, de modo de difundir dicha ciencia en el entorno escolar y al público en general.
Palabras clave: Evolución Estelar; Estrella; Diagrama H-R y Fusión Nuclear; Enseñanza de Astronomia.

1. Introduction

In Brazil, the concepts related to Astronomy are foreseen in the official documents of the Ministry of Education for the two levels of Basic Education (Damasceno, 2016; BNCC, 2017; PCN, 2000). However, these concepts are not well approached in educational institutions, sometimes due to negligence, sometimes due to lack of preparation, lack of materials, and several other reasons. In addition to the lack of subsidies for the teaching of Astronomy, there is also a lack of teacher training in the area (Langhi & Nardi, 2012), both initial and continued. Some of these teaching professionals, when they perceive this gap in their education, seek on their own to remedy this lack of knowledge on websites, media and even some textbooks with conceptual errors, which leads to the dissemination of wrong information about Astronomy (Langhi & Nardi, 2007; Langhi, 2011).

In this scenario, the need has arisen for the preparation of didactic materials that serve as subsidies, not only in teacher training, but that also help him in the classroom. In order to fulfill this need, in his term undergraduate dissertation, Xavier (2019) developed an information booklet based on a bibliographic review on Stellar Evolution, and used it as resource to give lectures and to held workshops on the theme, in educational environments located in the city of Marabá (PA). The aim of his work was to produce materials and methodologies that can help both teachers and students to consolidate the teaching and learning process in a mutual way (Xavier, 2019).

Taking this into account, in Section 2 of this paper is presented the main concepts of the area of stellar evolution, selected and discussed from a literature review about the evolutionary cycle of the stars, from the formation of the Protostar to hyper explosions of Black Holes; from the Molecular Clouds, the different evolutionary forms of burning nuclear fuel, the evolutionary stages in the HR Diagram, until the possible deaths of the stars. Then, in Section 3, the impressions taken from the experiences carried out in the city of Marabá (PA) are described, as a way of spreading Astronomy, from the knowledge systematized in the booklet. In Section 4 are presented the final considerations about this work.

2. Methodology

This work is divided into two parts. In the first one, it is presented a brief review of the key concepts about the stellar evolutionary process. It is a purely explanatory approach aiming to simplify the understanding of phenomena that are directly linked to stellar evolution, and to arouse the readers' interest on the subject of Astronomy and Astrophysics. It is presented in such a way that the different evolutionary phases and the factors that are responsible for them become clear, from the contraction of the molecular clouds giving rise to the protostar, until the moment of the star's death.

From this literature review it was elaborated an information booklet. Being a theoretical research, the approach used was qualitative. It was analyzed a series of literature materials realised between the years of 2000 and 2019, which makes this a vast bibliographic review on the subject, using books, articles and websites that are dedicated to explain the evolutionary processes in different ways. Thus, this work unifies all this literary framework of Astronomy in a single research to be used as reference. In addition, the images presented in the work are a visual stimulus to arouse the interest of the reader, and also facilitate the understanding of the progress of the evolutionary cycle of the stars. Our work is based on the conception of the author Pereira A.S. et al. (2018), who defends the interrelationship between science, technology and society as fundamental tool for the production of scientific knowledge in the last decades. In summary, the text presented in the first part of this work is basically the material that underlies the booklet used as a reference for the dissemination and scientific literacy in the teaching of Astronomy.

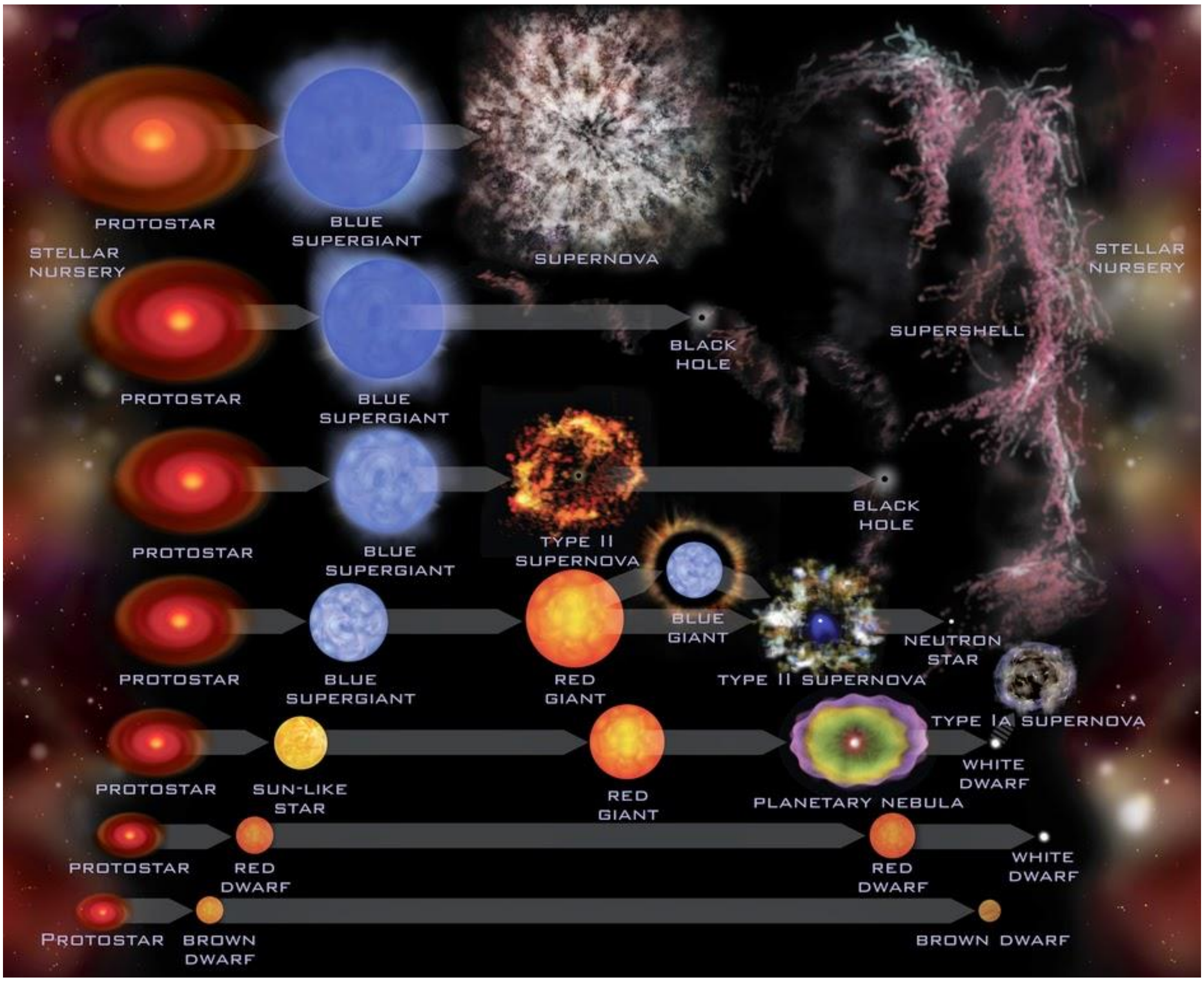
The second part of this work was dedicated to outreach activities and scientific dissemination, creating the opportunity to put into practice the knowledge acquired as a result of making the booklet and to use the contents of the booklet itself. Thus, several workshops were held in public schools in the region of Marabá, during which short courses and lectures took place, using materials taken from the booklet, which were transformed into slide shows.

These events took place in five educational institutions, including elementary, secondary and higher education institutions. The average number of students reached by these events was around 560. In order to carry out the short courses, we count on the collaboration of the teachers of each institution and the support of the Astronomy Center of Marabá (Núcleo de Astronomia de Marabá).

3. Theoretical Basis: Stellar cycle

By analyzing the evolutionary cycle of stars, it is possible to determine some aspects that can help in understanding the Universe, from its origin to its current expansion. Based on what is known about the Sun, it is possible to determine stellar parameters of other stars, such as mass, color, luminosity, chemical composition, stage of evolution, from spectroscopic and photometric analyzes. The evolution of a star can take, in some cases, billions of years (little massive stars) or millions of years (massive stars). As it is a long evolutionary period, astrophysicists study not only the evolutionary cycle of a single star, but of several stars in different evolutionary stages, through observations, mathematical models and computer simulations. Observe in figure 1, a representation of the evolutionary cycle of the stars, with the initial and final phases of evolution.

Figure 1: Diagram of the stellar life cycle.



Source: NASA (s/a).

Observe the different evolutionary phases of the stars in Figure 1.

In the next sections, each of the stages of evolution presented in Figure 1 will be addressed.

3.1 Molecular clouds: stellar nursery

The stars are formed in the so-called Stellar Nurseries, which are found in the giant Molecular Clouds. These clouds make up the equivalent of about 10% of the entire mass of the Milky Way, or also 10 billion suns, and they are composed of 80% Hydrogen, 18% Helium and 2% heavier elements, such as dust and grains of ice (Capelato, 2003). In addition, it is emphasized that they have low density and a low rate of productivity.

According to Xavier (2019), Molecular Clouds are remnants of the final stages of the evolutionary cycle: stars die to give lives to others. Because they have low density, most of these clouds are in the process of expansion, that is, the internal pressure of the cloud (due to the gas) is greater than the external pressure (due to gravity).

The star will only begin its formation process when, for some reason, the cloud starts to contract. This process can occur due to factors internal and external to the cloud. The internal factors are the supernova explosions that were generated in that same cloud and are in their final evolutionary stage. The external factors are the spiral arms of the Galaxy that produce intense distortions in the temporal mesh, that is, the arms exert great gravitational forces (Xavier, 2019).

3.2 Protostar

When the cloud starts the fragmentation process, all the denser particles inside it start to collide with each other, forming a cluster in the center of the cloud, which gives rise to the Protostar (Xavier, 2019).

The continuous contraction process increases the temperature and luminosity of the protostar (Guimarães, 2004). It is only when the radioactive nucleus reaches a temperature high enough to initiate nuclear reactions that the star is actually born (Kippenhahn, 1990). In this phase, Hydrogen will be consumed for years inside the star. In the following section the different processes for burning nuclear fuel are discussed.

3.3 Stellar Evolution

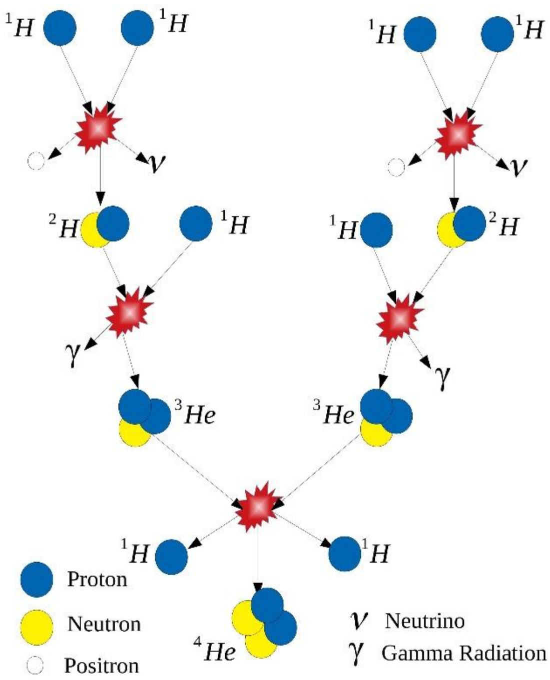
A star is only born when the amount of energy that is generated in its core is equal to that radiated on its surface. In turn, this energy is generated inside the star through nuclear reactions, where nuclei of light elements are fused to give rise to heavier elements.

This process can occur in three different ways: in the case of low-mass stars it occurs through the proton-proton chain; in the case of massive stars, this process happens through the carbon-nitrogen-oxygen cycle (CNO); and in the case of supermassive stars, energy is obtained through the triple-α process (Xavier, 2019).

3.3.1 Proton-proton chain

According to Xavier (2019), the proton-proton chain, also known as p-p chain, is the way low mass stars burn hydrogen in helium; these reactions occur at a temperature equivalent to $T \cong 8 \times 10^6 K$. Observe in Figure 2 how this reaction occurs.

Figure 2: p-p chain.



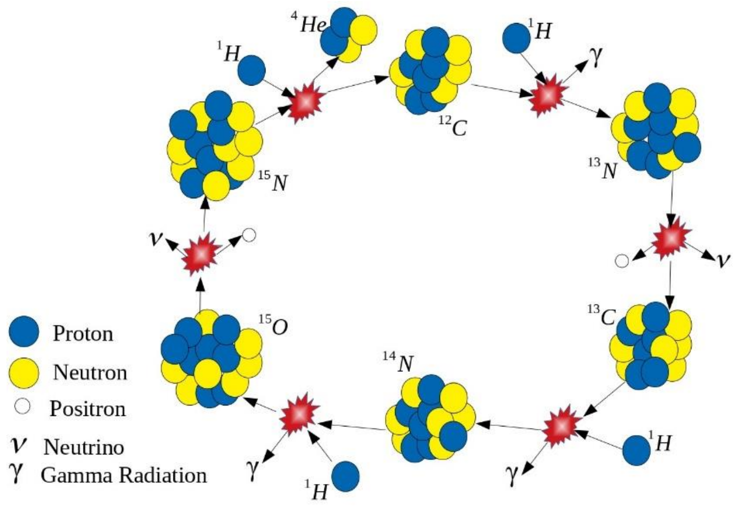
Source: Adapted from Steiner (2015).

Two hydrogen nuclei (two protons) are fused to give rise to the densest hydrogen, the so-called deuterium, releasing a positron and a neutrino. After this reaction, a deuterium and a hydrogen nucleus fuse to generate ^{3}He (helium) releasing gamma radiation (γ). Then, two cores of ^{3}He fuse, creating a ^{4}He (alpha particle) and two protons; the star repeats this cycle until it consumes all its hydrogen mass, leaving only helium in its core, and then it will begin a new evolutionary stage.

3.3.2 CNO Cycle

Stars more massive than 0.8 solar masses fuse hydrogen into helium differently from the one presented in the previous section, as they use isotopes of carbon (C), nitrogen (N) and oxygen (O) as catalysts for the production of ^{4}He. These reactions occur at a temperature of $T_c \geq 18 \times 10^6 K$ (Xavier, 2019). Observe the representation of these reactions in Figure 3.

Figure 3: CNO cycle.



Source: Adapted from Steiner (2015).

An H nucleus is fused with one of ^{15}N. Soon, this isotope will become ^{12}C, releasing a positron, which quickly annihilates with an electron, and a neutrino, which will come out of the star carrying some energy. When another H collides with this isotope, gamma radiation will be released again and the element will become a ^{14}N. Merging another proton (H nucleus) with the latter, which will give rise to a ^{15}O releasing more radiation, the element will quickly decay, releasing a positron and a neutrino, turning again into a ^{15}N. This process will continue until only ^4He inside the star.

3.3.3 Triple-α Process

When stars that left the Main Sequence, after going through the CNO Cycle, consume all the H stock, the star's nucleus becomes made up of alpha particles (^{4}He), and the nuclear reactions that occur with these particles are called Triple-α Process, where three nuclei of ^4He merge to give rise to the ^{12}C (Xavier, 2019). Observe in Figure 4 the representation of these reactions.

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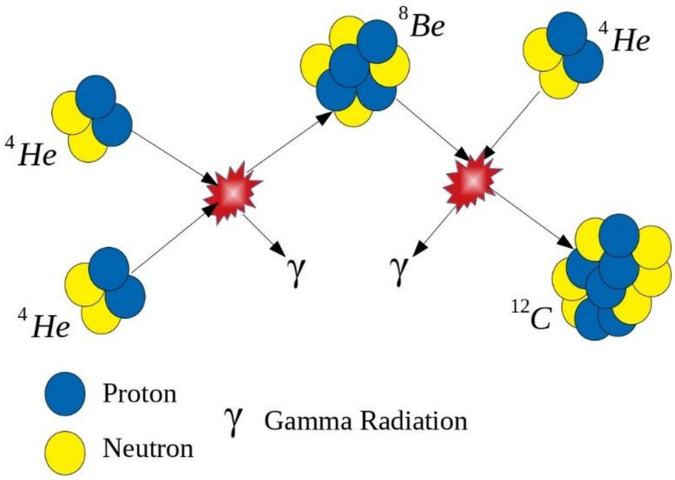
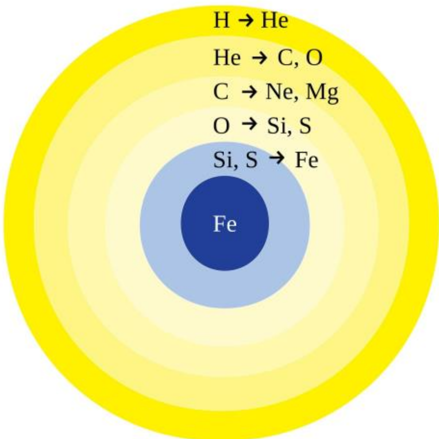
Figure 4: Triple-α process.



Source: Adapted from Steiner (2015).

These reactions will occur until only heavier elements remain inside the star. According to Ortiz (2014), the elements with higher atomic numbers (heavier) are closer to the nucleus, as shown in Figure 5.

Figure 5: Distribution of elements.



Source: Adapted from Steiner (2015).

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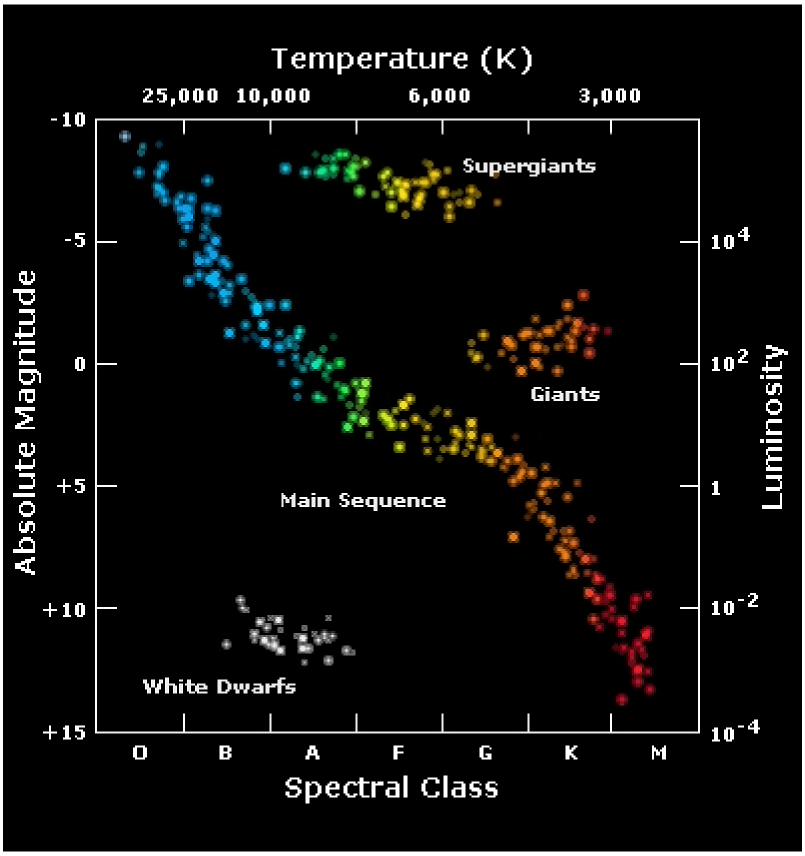
3.4 Hertzsprung-Russell Diagram

Visually, the most evident characteristics of the stars are their color and brightness, which are directly linked to their mass (Xavier, 2019). Given this relationship (color *versus* brightness), the Hertzsprung-Russell Diagram appears (Figure 6).

Figure 6: Hestzprung-Russel diagram.



Source: Iowa University (2017).

The Hertzsprung-Russel Diagram, or H-R Diagram, is a graph that shows the distribution of stars according to two of their characteristics, such as: color versus luminosity, which allows to obtain information about other characteristics of the stars, such as their mass, temperature and spectral type (Xavier, 2019). It is worth mentioning that the diagram is not a map, because the stars are not distributed like that in the Universe, they were only cataloged according to their characteristics.

This diagram was developed, independently, by the Danish Ejnar Hertzsprung (1873-1967), and by the American Henry Russel (1877-1957), in 1911 and 1913, respectively (S.O. Kepler & Saraiva, 2017).

See Figure 6. On the x-axis, from left to right, there is the temperature distribution, which ranges from 2000 K to 30000 K. On the y-axis, from bottom to top, we have the luminosity scale that varies from 10^{-4} to 10^{-6}; so, the higher the star is in the diagram, the brighter it will be. On the right side of the diagram is the mass distribution; the higher up the star is in the diagram, the more massive it will be.

The strip that crosses the entire graph diagonally is known as the Main Sequence (MS). According to Percy (2012), most of the stars are found in SP, where they will spend a large part of their lives burning H in He.

Above the SP are the *Red Giants and Supergiants*, which are stars that have already consumed all their stock of H and started to burn heavier elements such as He and C.

Below the MS are the *White Dwarfs*; these are stars that didn't get enough energy to burn heavier elements such as C.

3.5 Evolution of stars with a mass below 0.5 solar masses: red dwarfs

According to S.O. Kepler and Saraiva (2017), stars with masses below 0.5 solar mass become red dwarfs. Due to their low mass, these stars are unable to exert sufficient pressure on their cores to start burning helium, even though they have burned all their hydrogen storages. The less massive the star, the longer its life span: red dwarfs of 0.1 solar mass remain in MS for about 6×10^{12} years, while more massive dwarfs, remain in the MS for around 6×10^9 years.

3.6 Evolution of stars with mass between 0.5 and 10 solar masses

In stars with a mass between 0.5 and 10 solar masses, due to the high pressure in their interiors, the core is already large enough to start burning helium when still burning the hydrogen layer. These stars will become red giants in one of the stages of stellar evolution. These are stars with immense radius and low surface temperatures, about 5,000 K. Among these stars, the best known are those that belong to the red giant branch, as seen in Figure 6.

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At this stage, their shells are still fusing hydrogen into helium, while their core is of inert helium (SO Kepler & Saraiva, 2017). After this phase, this type of star will evolve into a planetary nebula and white dwarf.

3.6.1 Red Giants

When the star reaches this stage of evolution, it has already consumed all its H stock, and its core is predominantly formed by of alpha particles (^4He). To continue the evolution process, the star increases its temperature and radius, becoming a Red Giant, reaching internal temperatures of $T_c \geq 10^8 K$ (Xavier, 2019).

According to Guimarães (2004), in this phase the star is cold and luminous. Because its radius has increased, the surface temperature of the star is in the range of $T = 4 \times 10^3 K$, and its luminosity is thousands of times higher than that of the Sun. Observe in Figure 7 the comparison of size between a red giant and the Sun.

Stars with mass below 0.8 solar masses do not have enough thermonuclear fuel in their core to ignite their evolution, and therefore become white dwarfs (as seen in Figure 6) until it completely cooled down, disappearing into the darkness of the Universe. Intermediate mass stars (greater than 0.8 solar masses) evolve to the point of launching their outer layers like a planetary nebula. Figure 7 illustrates the size comparison between the Sun and Aldebaran.

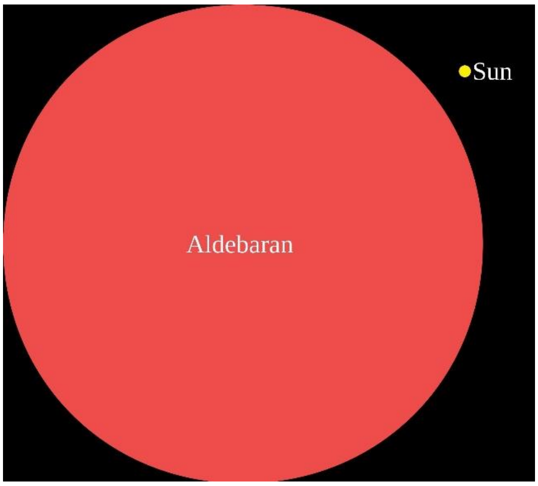

Figure 7: Size comparison between the red giant star Aldebaran and the Sun.

Source: Prepared by the authors.

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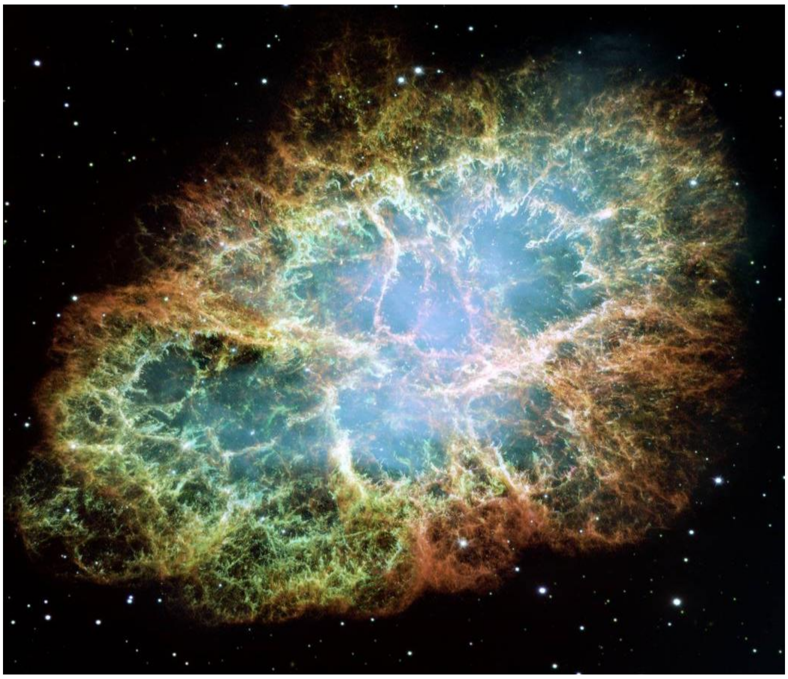
3.6.2 Planetary Nebula

Stars that failed to burn heavy elements end their evolution as a Planetary Nebula, with a White Dwarf at its center. This is due to the nuclear reactions ceasing inside the star, leaving only an inert core, causing gravitational instability, which in turn produces intense winds of neutrinos that disperse the outermost layers of the stellar core, giving rise to the Nebula (Xavier, 2019).

These nebulae originate large molecular clouds, which, in turn, will give life to new stars that will continue this evolutionary cycle.

Figure 8 shows the representation of the supernova remnant called the Crab Nebula, a Planetary Nebula. Note that the ejected material will be recycled to form new stars, continuing the stellar life cycle.

Figure 8: Representation of the Crab Nebula.



Source: NASA (2017).

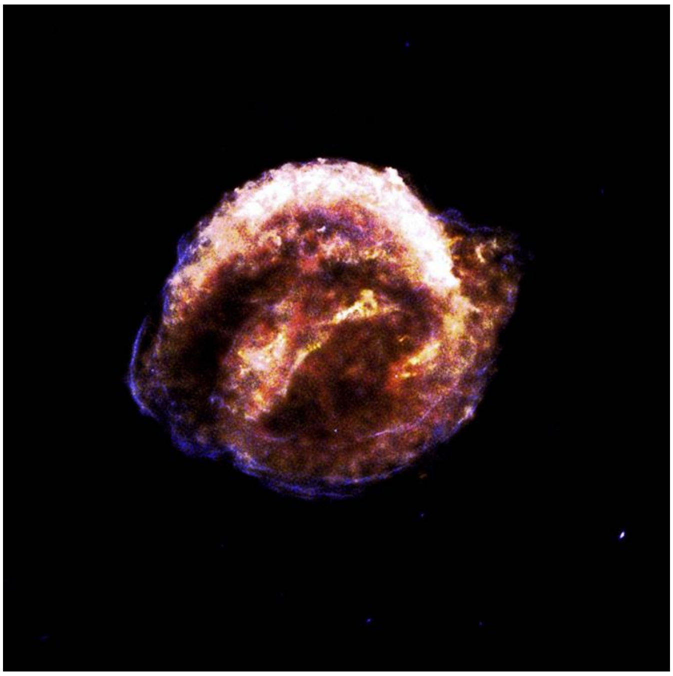
3.7 Evolution of stars with mass greater than 10 solar masses: Supernova

In the case of stars more massive than 10 solar masses, the fusion of lighter elements into heavier ones occurs until its iron core becomes so dense that it cannot support its own mass. When this happens, the stellar core suddenly collapses, forming neutrons and neutrinos. The impact caused by this sudden collapse causes the star to explode in a type II supernova[1] (S. O. Kepler & Saraiva, 2017).

Massive stars explode in type II supernovae; however, it is possible that a star system with masses between 0.1 and 0.5 solar masses will also become a supernova, so-called type I supernova (Xavier, 2019).

For the described above process to occur, it is necessary to have mass transfer between the stellar system, until one of them gets enough mass to start burning heavy elements (Ortiz, 2014). Figure 9 shows the remnant of Kepler's supernova, in which is observed one of the finals stages of the stellar evolutionary cycle.

Figure 9: Representation of the Kepler Supernova Remnant.



Source: NASA (2020).

[1] Type II supernovae are less luminous and take relatively less time to collapse than type I supernovae, on the other hand, the duration of the type I supernova is shorter than that of type II.

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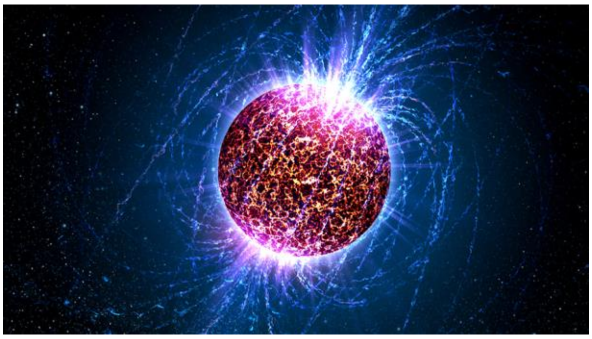
3.7.1 Neutron Star

After the explosion of a supernova, the ejected matter turns into a planetary nebula, however, the supernova core still remains. When the mass of this nucleus is greater than 1.5 solar masses, the density becomes so great that the pressure is no longer sufficient to maintain stability. The electrons start to collide with the protons, becoming neutrons, giving rise to the neutron star. According to Capelato (2003), these stars are relatively small, have a radius around 10 km, density close to 1,000 trillion g/cm^3 and a magnetic field of 10^{12} gauss; in some cases, they become pulsars, an especial case of neutron stars, which will be seen in the following section. In Figure 10, the illustration of a Neutron Star is shown, and in it we can see its intense magnetic field.

Figure 10: Representation of a Neutron Star.



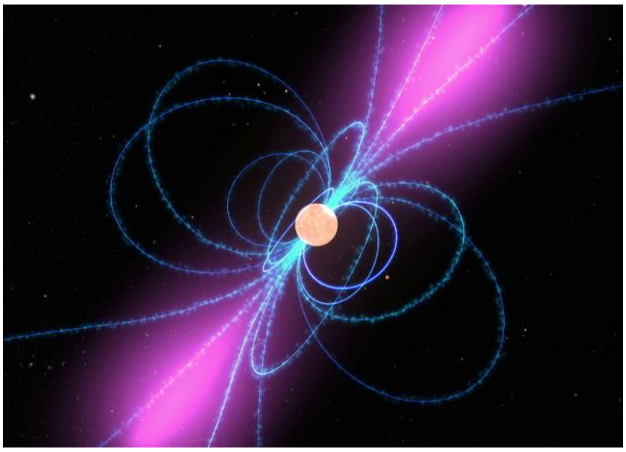
Source: Hypescience (2018).

3.7.2 Pulsars

Pulsars are neutron stars that have unique characteristics that differentiate them from ordinary neutron stars; due to their intense magnetic field, they transform rotational energy into electromagnetic energy (Xavier, 2019).

According to Xavier (2019), through its rotation, its intense magnetic field induces a huge electric field on its surface. In turn, this electric field is sufficient to pull charged particles off the surface, mostly electrons, that flow into the magnetosphere, where they are accelerated. These accelerated electrons emit synchrotron radiation in a narrow beam along the lines of the magnetic field. Observe in Figure 11 the representation of a pulsar.

Figure 11: Pulsar.



Source: NASA (2008).

Figure 11 shows the representation of a Pulsar in which we can observe the star spinning rapidly, ejecting matter into space in the form of radiation.

3.7.3 Black Hole

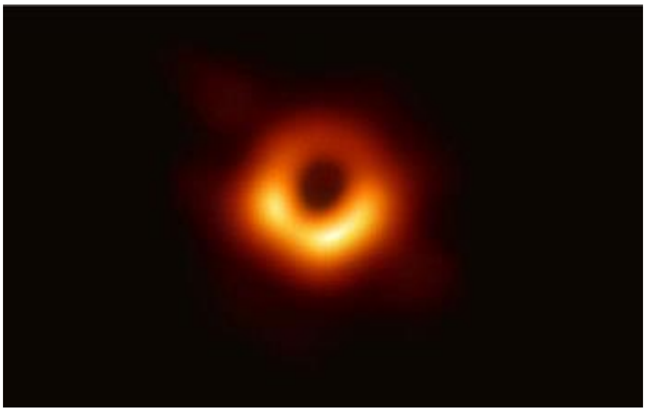
When the neutron star exceeds 0.3 solar masses, gravity becomes so intense that the neutron matter cannot support it and collapses again, creating a singularity in space-time, known as a Black Hole. This object causes a great curvature in space-time that even light cannot escape. Light can come in, but it can't come out (Sitko & Miyahara, 2011).

Black Holes have an external part known as Event Horizon, from which not even photons can escape (Ortiz, 2014).

These objects are called *black* because they do not emit or reflect light, however, there is a theory according to which it is predicted that black holes release black-body radiation due to quantum effects near the event horizon, the so-called Hawking radiation (Santi & Santarelli, 2019).

See in Figure 12 the real image of a black hole, taken on April 10, 2019[2].

Figure 12: Real image of a Black Hole.



Source: National Science Foundation (2019).

As we can see in this section, stellar evolution involves a series of concepts, processes and terminology that the teacher needs to be familiar with, in order to use them successfully in his classes or in outreach lectures. Therefore, the conception and elaboration of the information booklet on Stellar Evolution is justified. Not only because it was written in a language more accessible to this audience but also because it fills a gap in this area in Brazil. The next section describes the experience with the use of this booklet as didactic material for the dissemination of scientific knowledge in the city of Marabá, in the state of Pará.

4. The Dissemination of Knowledge on Stellar Evolution in Marabá-PA and the Teaching of Astronomy

As a way of disseminating Astronomy, and also, in a way, applying the elaborated information booklet, lectures, workshops and short courses were held in schools and universities in the city of Marabá, reaching more than 500 students, and, indirectly, also many teachers.

The proposal taken to these educational environments was intended to introduce the basic concepts related to the field of Astronomy, as a way to assist and motivate student

[2] For a complete overview of the first image made of a black hole, see Matsuura (2020).

participation in the Brazilian Astronomy and Astronautics Olympics (Olimpíada Brasileira de Astronomia e Astronáutica – OBA, in portuguese), and also to motivate their participation in the Science, in general. To develop and carry out such activities, it was possible to count on the support of the Astronomy Center, the Federal University of the South and Southeast of Pará, as well as the teachers of the schools involved.

What could be observed during the application of the activities and lectures was the great participation and motivation of the students of the ninth year of Basic Education. Many reports and doubts about the OBA were heard, which showed a great interest of students in the area, contrasting with the great scarcity of access to Astronomy that they have.

In Brazil, the field of Natural Sciences, in general, has been marginalized in Education (even in Higher Education), and, in particular, Astronomy is not only marginalized, but often completely omitted from the curriculum, or even, taught in an erroneous way (Langhi & Nardi, 2007).

In order to contribute to the change in this cultural paradigm in schools, it was proposed to prepare the information booklet, to assist teachers and students with teaching and learning about Stellar Evolution, as well as visits were made to schools and other educational environments, in the city of Marabá (PA), in order to disseminate this motivating and inspiring science, seeking to attract students' interest in Astronomy.

Awakening the student's investigative interest and making him seek to research more and more in order to build knowledge on the topic is the greatest challenge of our work.

5 Final Considerations

In this work, an information booklet about the evolutionary cycle of the stars was elaborated, based on a bibliographic review. The subject is addressed from the composition of the cloud to the composition of the molecular cloud, addressing the main factors that influence the formation of the protostar in stellar nurseries, the different ways in which stars generate energy within their interiors, their different evolutionary paths, until the final stages of this evolution. Thus, the information booklet can be used as reference material to assist both in Astronomy Teaching during classes as well as in scientific outreach.

The production of didactic material is essential not only to give basis to students, but also to guide teachers who can count on subsidies to teach a good class, always thinking about improving teaching methodologies, provided that the Physics teaching (and Science, in general) in the country is one of the most needy. Considering that in Brazil the basic concepts related to Astronomy are foreseen in both the National Curricular Parameters (Parâmetros Curriculares Nacionais - PCNs, in portuguese) and the National Curricular Common Base (Base Nacional Comum Curricular - BNCC, in portuguese) for the two levels of Basic Education, and also the lack that exists in the market of good references on the subject in Portuguese, this work contributes to the production of didactic material, and further to promote its use.

In addition, the subsidies created by materials such as the one elaborated here may help both in the academic training of teachers, as well as in proposing methodologies and themes to be addressed in the classroom, providing conditions for improvement in Brazilian scientific education.

Finally, as future perspectives for this work, we hope to build didactic proposals and guidelines on how to approach the content discussed here in high school, and engage young students in scientific discussions, preparing them for higher education in the fields of science and technology.

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