The Metallicity of the Sun Reviewed from Pre-Main Sequence Evolution

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Abstract: Metallicity is defined as the fraction of the abundance of elements heavier than hydrogen and helium. Metallicity has different values for different stellar objects and its value will also change as the star evolves. This research is focused on calculating and analyzing the early metallicity of the Sun, that is at the beginning of the Sun's evolution at the Pre-Main Sequence. Five metallicity samples with an initial mass of 1 $M_\odot$ were used. This study uses the evolution code MESA r-15140 which produces a Hertzsprung-Russell diagram with various metallicities. From the simulation, it is found that the most suitable metallicity is 0.065. There are four dominant elements at the core of the Sun, namely hydrogen, helium, carbon, and oxygen. The density, pressure, and temperature values at the core of the Sun also increase with age.

Keywords: Metallicity; Sun; Pre-Main Sequence Evolution; MESA

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Article history: Received 15 April 2022, Accepted 26 September 2022, Published Oktober 2022.
http://dx.doi.org/10.12962/j24604682.v18i3.12791

I. INTRODUCTION

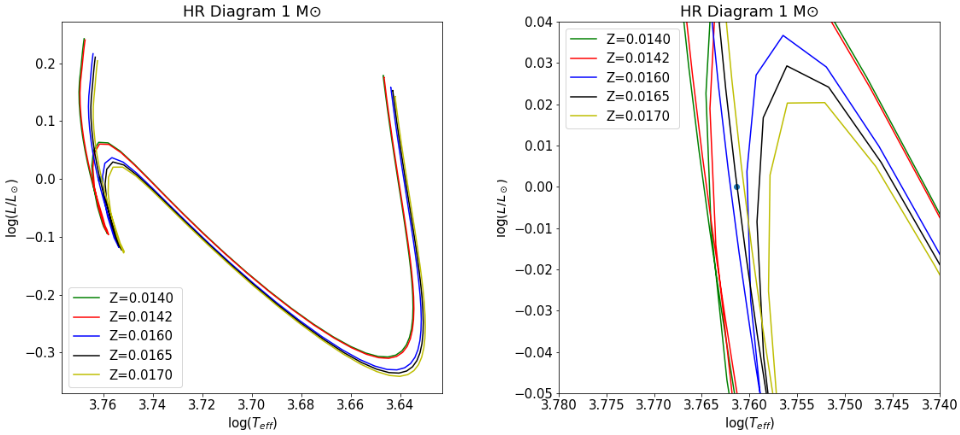
Metallicity is a fraction of the abundance of the heavier elements than hydrogen and helium which can be symbolized by Z, while hydrogen and helium are usually symbolized by X and Y. The relationship between these three abundance parameters is

$$X + Y + Z = 1 \tag{1}$$

Each star has a different metallicity value. The environment in which a star is formed is one of the important factors that determine the metallicity of a star. The metallicity value of a star is not constant, Z will change as the star evolves. Several methods can be used to calculate the Z value, among others are from photospheric spectroscopy observations, helioseismology, and observations of the solar wind. It can be reviewed from [1] some values obtained for the solar metallicity, among others are 0.0202 from spectroscopic observations of the Sun, 0.0245±0.001 from helioseismology using the abundance of the helium, and 0.0196±0.0014 from the measurement of heavy particles of the solar wind using a *Solar Wind Ion Composition Spectrometer*.

During their lives, stars experienced some evolution phases. Generally, it is divided to three main phases, namely Pre-Main Sequence, Main Sequence, and post Main Sequence phases. Our research will focus on the evolution of the Sun from the Pre-Main Sequence phase to its present phase as a Main Sequence star due to the changing in metallicity with the course of evolution. Star formation starts from interstellar clouds or interstellar medium (ISM) which has a very low density, very large volume, and very light mass. At the beginning of star formation, gravity plays a very important role. When there is a disturbance, the ISM will compress and the outside of the ISM will be pulled inward by gravity, this process is called condensation. The disturbance possibly come from shock waves from a supernova explosion or a collision with another cloud. The condition that must be met for a star to condense is to have a mass limit called the *Jeans* mass. Clouds with a mass greater than *Jeans* mass will not be able to maintain hydrostatic equilibrium and will shrink. Then there will be fragmentation, the cloud splits into many smaller pieces and each cloud undergoes gravitational shrinkage until the star temperature becomes high enough and becomes a protostar. This is where we start the Pre-Main Sequence phase.

The evolution of stars is usually depicted on the Hertzsprung-Russell (HR) diagram. The vertical axis in this diagram represents the luminosity value and the horizontal axis represents the effective temperature value which increases to the left. At first, when the Sun was still a protostar, its temperature and luminosity were still very low. At this low temperature, hydrogen is found in the form of H_2 molecules. Due to the pressure and collisions between molecules that occur more frequently, the temperature increases. There is an important line in the HR diagram, namely the Hayashi line/track, which marks a star in a state of perfect convection when it was in the Pre-Main Sequence evolution phase. Protostars that do not have a sufficiently high temperature and cannot maintain their hydrostatic equilibrium cannot cross this line, so they cannot continue their evolution to the next stage. The area of protostars before they cross the Hayashi line is called the Hayashi forbidden zone. The Sun, which was still



(a) (b)

FIG. 1: (a) Pre-Main Sequence phase of the Sun on the HR diagram. Each line represents different metallicity: 0.0140, 0.0142, 0.0160, 0.0165, 0.0170. (b): We zoom in the image (a) to show the track with suitable metallicity for the Sun. The blue dot is the reference point for the Sun's current location on the HR diagram with $\log L/L_{\odot} = 0$ and $\log T = 3.7613$ [2].

a protostar, must be able to cross the Hayashi line to continue its evolution.

Protostars that follow Hayashi track still have low temperatures so that almost all stars are in a convective state. The temperature of the star will keep getting hotter so that the center of the star will be in radiative equilibrium. As more energy is transported radiatively, the luminosity and temperature of the star will also increase. At this stage, the evolutionary rate is much slower, and the convective envelope decreases with the increase in the radiative core. Contractions in protostars continue, according to the virial theorem, until the central temperature becomes high enough for hydrogen combustion to occur. When the hydrogen burns and fusion energy is generated, the star stops contracting and evolves into a star starting at the *Zero Age Main Sequence* (ZAMS) point which also marks the start of the evolutionary phase in the Main Sequence. At present, the Sun is still in this Main Sequence phase, with a luminosity of $L = 3.828 \times 10^{26} W$ and an effective temperature, $T = 5772K$ [2].

In this study, the metallicity will be determined based on the reference data of the current solar parameters and analyzed for temperature, pressure, and density. Part two of this article describes the research method, followed by the results and analysis in part three, and conclusions in part four.

II. RESEARCH METHOD

To determine the most suitable metallicity for the current state of the Sun, a modeling of the evolution of the star from the Pre-Main Sequence phase is carried out, assuming the Sun's initial mass is the same as the current mass of 1 $M_{\odot}$, with five metallicity values. The current position of the Sun on the Main Sequence, with luminosity and effective temperature values of $3.828 \times 10^{26} W$ and 5772 K, is used as a reference to obtain an evolutionary track that corresponds to the metallicity value used in the model.

The instrument used in this study is *Modules for Experiment in Stellar Astrophysics release* 15140 (MESA r-15140). MESA is an open-source 1D stellar evolution code which is regularly updated (see [3] for the latest updated version). With some input parameters needed in modeling the evolution of stars, we then obtain 53 related parameters which can be processed and analyzed further. In our model, as the input parameters, we have stellar mass, metallicity, and convective coefficient. From the output of the modelling, we analyze some parameters, such as effective temperature, luminosity, abundance of elements resulted from the fusion reactions in stellar center, age of the star during the evolution, and other parameters of the stellar center (density, temperature, pressure) to explain further about the evolution of the Sun.

III. MESA R-15140 INPUT

The MESA r-15140 provides a variety of inputs that can be tailored to fit each need. In this study, the input parameters are stellar mass $M = M_{\odot}$ (solar like star) as the initial mass of the Sun, metallicity values $Z = 0.0140,\ 0.0142,\ 0.0160,\ 0.0165,\ 0.0170$ (there are some values suggested as the solar metallicities (see [1] and references in)), and convective coefficient α_{MLT}, which is a parameter used to describe convection phenomena on the Sun, is 1.8 [4].

IV. RESULTS AND DISCUSSION

The metallicity of the Sun in the Pre-Main Sequence phase is different from the metallicity in the Main Sequence. There

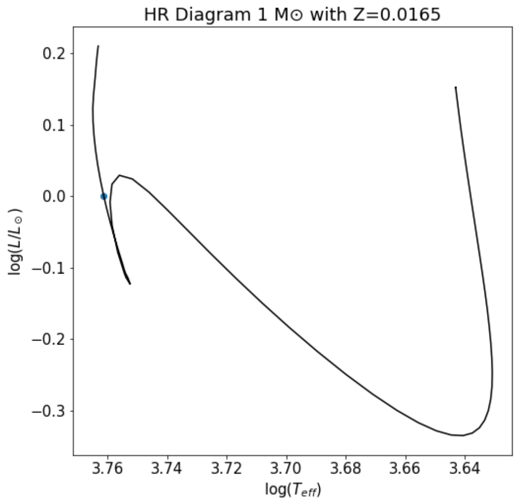


FIG. 2: Pre-Main Sequence phase of the Sun on the HR diagram for $Z = 0.0165$.

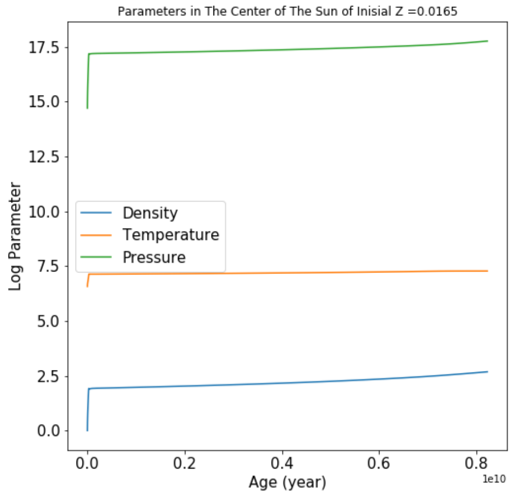


FIG. 4: The changes of density, temperature, and pressure at the center of the Sun during the Pre-Main Sequence phase.

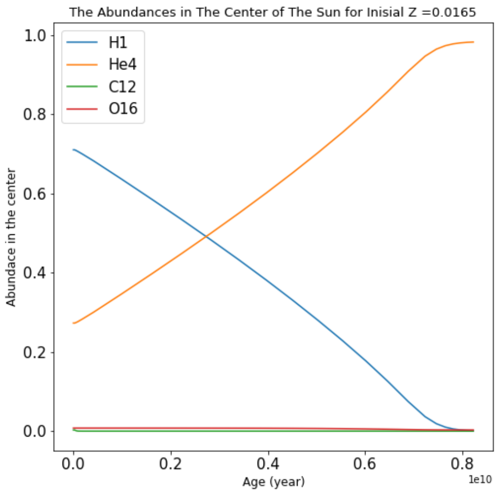


FIG. 3: The changes of chemical elements abundances at the center of the Sun with time.

are two candidates of metallicity values of the Sun when it was still a protostar, namely $Z_{protostar} = 0.0142$ [1] and 0.0140 [5]. From these two values, the HR diagram for the Sun is obtained (Fig. 1(a)).

In Fig. 1(a), we found that there is no line either from $Z_{protostar} = 0.0140$ (black line) or 0.0142 (red line) that passes the Sun's current reference point. Therefore, we perform an analysis using several metallicities to obtain a line that passes through the reference point by using the other metallicities namely 0.0160, 0.0165, and 0.0170. From these metallicities, we found that $Z_{protostar} = 0.0165$ is suitable as a candidate for the metallicity of the Sun in the Pre-Main Sequence phase because the graph in the HR diagram passes through the reference point.

By using the parameters mentioned in section 3 with $Z_{protostar} = 0.0165$, we get the Sun evolutionary track on the HR diagram in Fig. 2, starts from the Pre-Main Sequence phase, after crossing the Hayashi line from the Hayashi forbidden zone which is depicted to the zone with both very low effective temperature and luminosity (at the low left of the Fig. 2), to the end of Main Sequence phase. The protosun then traced Hayashi line vertically. At this time, the luminosity of the protosun decreased with a relatively constant temperature.

The modeling results also provide information about changes in the abundance of elements in the core of stars during evolution. This abundance depends on nuclear combustion that occurred during evolution. Fig. 3 shows the evolution of elemental abundance in the core of the Sun.

Four elements were produced in this modeling, namely hydrogen, helium, carbon, and oxygen. From Fig. 3, it can be seen that only hydrogen and helium underwent significant changes.

At the beginning of its age, the Sun was dominated by hydrogen. Due to the contraction that occurred while as a protosun, the temperature in the Sun's core increased, resulting in the burning of deuterium. The abundance of helium increases with the combustion of deuterium. This is shown in Fig. 3 that the abundance of helium increases with the decrease of hydrogen. With the burning of deuterium in its core, the temperature of the protosun also increased. Before reaching the Main Sequence, all deuterium had been converted to helium, and by the time the core temperature reached $T_{center} \sim 1.38 \times 10^7$ K, the protosun started the hydrogen burning reaction and marked the beginning of the Main Sequence phase of evolution.

Other parameters at the center of the Sun also underwent changes during the Pre-Main Sequence evolution phase. This is shown in Fig. 4 for the changing of the density, temperature, and pressure.

The values of these three parameters increase with the age of the Sun. The gradients of the three graphs also have different steepness, with density and pressure having greater steepness than temperature. These are related to convection events that occur in the Sun, especially when the protosun follows the Hayashi line downwards. The Sun is in the adiabatic phase [6] which can be showed from the ideal gas equation,

$$\nabla = \nabla_{ad} \quad (2)$$

$$P = K\rho^{\frac{5}{3}} \quad (3)$$

The temperature of the protosun, when it followed the Hayashi track, only experienced a much smaller increase in pressure and density. Deuterium combustion caused a rapid increase in density, followed by a rapid increase in central pressure. This increase continued until the protosun reached the Main Sequence phase.

V. CONCLUSION

From the Sun's current luminosity and temperature, we found that the most suitable metallicity for the Sun in the Pre-Main Sequence phase is 0.0165. This metallicity will increase with the increasing age of the Sun. This increase is directly related to the evolution of the abundance of elements present in the Sun. From the modeling we made, there are four most dominant elements in the evolution Sun from pre to the end of Main Sequence phase, namely hydrogen, helium, carbon, and oxygen. The density, temperature, and pressure also change during the evolution of the Sun. All three increase with age with different gradient slopes.

Acknowledgment

We thank to ITB for supporting this work as part of research project in master program in astronomy.

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