NUCLEOSYNTHESIS AND EVOLUTION OF LOW AND INTERMEDIATE MASS STARS

A Project Report

submitted by

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(Reg.No.: 1602200006)

in partial fulfilment of the requirements for the degree of

Master of Science
(Space Science & Technology)

under the guidance of

Dr. Aruna Goswami

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CERTIFICATE

Certified that the project report entitled **'Nucleosynthesis & Evolution of Low- & Intermediate- Mass Stars'** submitted in partial fulfilment of the requirements for the degree of Master of Science in Space Science & Technology is an authentic record of the work done by **Manu B Jayan** (Reg.No.: 1602200006) under the guidance of **Dr. Aruna Goswami**, Associate Professor, Indian Institute of Astrophysics (IIA), Bengaluru, during the period January-February 2018.

Head of the Department

External Examiners:

DECLARATION

I hereby declare that the project report entitled **'Nucleosynthesis & Evolution of Low- & Intermediate- Mass Stars'** submitted to Department of Space Science & Technology, St. Albert's College (Autonomous), Ernakulam in partial fulfilment of the requirement for the award of degree of **Master of Science** in **Space Science & Technology** is a record of the work done by me under the guidance of **Dr. Aruna Goswami**, Associate Professor, Indian Institute of Astrophysics (IIA), Bengaluru, during the period January-February 2018.

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Manu B Jayan

ABSTRACT

Low- and intermediate- mass stars constitute the largest number of all stars ($\sim 90\%$) in our galaxy. These stars pass throug Asymptotic Giant Branch (AGB) phase of evolution where some major nucleosynthesis processes take place and many important elements are produced. These stars contribute significantly to the galactic chemical enrichment with the products of these nucleosynthesis events. Low- and intermediate- mass stars pass through different evolutionary stages including the AGB phase and end as white dwarfs at the end of their evolution. In this project we have attempted to understand various nuclear burning processes and the evolutionary phases they go through in their journey from birth (i.e, from the main sequence stage) to death (i.e, white dwarf stage).

Contents

1 Introduction

There are 4 major star formation theories - collapse under gravity, random accretion, condensation and galactic nuclei activity. Of these, the collapse under gravity is the most widely accepted and believed theories among scientists working on this field. In this section, we briefly describe the formation of stars.

1.1 From Gas to Te-Tauri Stars

Stars take birth in stellar nurseries which are dense clouds of dust and gas. These clouds are extremely cold (temparature ranging between 10K and 20K) and can exist only as molecules owing to this extreme low temperature. They are very dense and are hence opaque to visible light. Thus these clouds are also called as dark nebula. But they can be detected using infrared or radio telescopes.

Initially the clouds would be at a state of hydrostatic equlibrium (i.e., kinetic energy of gas pressure balances internal gravitational force). This balance can be expressed using virial theorem according to which the gravitational potential energy must be twice the internal energy. If the cloud mass is greater than Jeans mass, then these conditions are not met and the cloud undergoes collapse. Greater the mass, smaller the size, colder the temperature, then less stable the cloud is against collapse.

Large clouds break into small clouds which then again collapses to much smaller fragments. These fragments may collapse further and angular momentum starts acting on them causing a spin motion. As the cloud undergoes collision, the density increases (starting from the centre), resulting in an increase in temperature and pressure. Slowly the cloud becomes very hot and starts acting as an IR source. By the time the cloud becomes a rotating disk, they would be surrounded by thick dust and gas and hence their detection becomes almost impossible.

The central region of the disk becomes a protostar and the nebular disk becomes planetory system. Matter is still absorbed into the core of protostar until pressure prevents this intake making the star stable. At a later stage thermonuclear fusion starts accompanied by strong stellar winds. The protostar has now become a Te-Tauri star. Though this stage is characterised by nucleosynthesis, the star is still in its early phase or pre-main sequence. Te-Tauri stars are higly active with bipolar outflows i.e., strong stellar winds emerging out from the two poles, along the axis of rotation. They are also characterised by vigorous surface activity (flares and erruptions) and has variable and irregular light curves. A Te-Tauri star sheds almost 50% its mass and finally settles down as a main-sequence star.

Initial mass ($M_\odot$)	Main-sequence lifetime	Total stellar lifetime
25	6.7 Myr	7.5 Myr
15	11 Myr	13 Myr
5	78 Myr	102 Myr
2	0.87 Gyr	1.2 Gyr
1	9.2 Gyr	12 Gyr
0.8	20 Gyr	32 Gyr

Table 1: Stellar lifetimes for stars of initial masses between 0.8 to $25M_\odot$. Lifetimes are given in Myr, which is units of 10^6 years, or in Gyr, which is units of 10^9 years (Karakas, 2010)

2 Some Preliminaries

Stellar nucleosynthesis is the process by which the natural abundances of the chemical elements within stars change due to nuclear fusion reactions in the cores and their overlying mantles.

Here, we will refer to low-mass stars as stars with initial masses between 0.8 to $2.25M_\odot$, and intermediate-mass stars as stars with an initial masses between $2.25M_\odot$ and $8M_\odot$ (Karakas, 2010). The dividing mass which separates low and intermediate mass is not arbitrarily chosen. The lower mass limit of $0.8M_\odot$ is the minimum mass required to ignite helium and evolve through central helium burning. The upper mass limit of $8M_\odot$ is the maximum mass which avoids core carbon ignition.

It is also important to have an idea about the different stages through which these stars travel. A Te-Tauri star becomes a main-sequence star which then ascends the first giant branch (FGB)and then moves to horizontal branch. Since the stars in this mass range do not have enough temperature required for core carbon burning, they ascend the asymptotic giant branch (AGB). Stars with initial masses between 9-$11M_\odot$ may also become AGB stars after core carbon burning; these objects are referred to as super-AGB stars. Stars more massive than about $11M_\odot$ evolve through the central carbon, neon, oxygen and silicon burning stages and end their lives as core collapse supernovae. Low and intermediate mass stars then enters the post-main sequence phase before settling in as a white dwarf.

The distribution of stellar birth masses is governed by the initial mass function. Majority ($\sim$90%) of the stars in the local solar neighbourhood have mass less than $0.8M_\odot$ and the remainder of the stars (about 10%) have masses between about 0.8 to $8M_\odot$

The most important period in the life of a star is the time it spends on the main sequence, fusing hydrogen to helium in the core. This is because it is the longest lived phase of stellar evolution and therefore representative of the entire nuclear burning lifetime of a star. Main sequence and total stellar lifetime for a selection of initial stellar masses is shown in Table 1.

Stars progressively enrich the interstellar medium with the products of stellar nucleosynthesis. This occurs because massive stars explode as supernovae, releasing vast quantities of processed material, whereas lower mass stars like our Sun slowly lose their outer envelopes by stellar winds. It is very much clear from the table that a low mass star has a longer life time than a heavy mass star. As the mass increases, so does the gravitational pull. In order to remain in hydrostatic equlibrium the radiation pressure must be increased. Star achieves this by increasing the rate of fuel consumption at the core leading to increased nuclear fusion that causes decrease in its lifetime. Lower mass stars, on the other hand, evolve and die much more slowly. Stars less massive than $0.8M_{\odot}$ will spend so long on the main sequence that they will not have had a chance to evolve and release their processed material into the interstellar medium. These very-low mass stars have not yet contributed to the chemical enrichment of our galaxy.

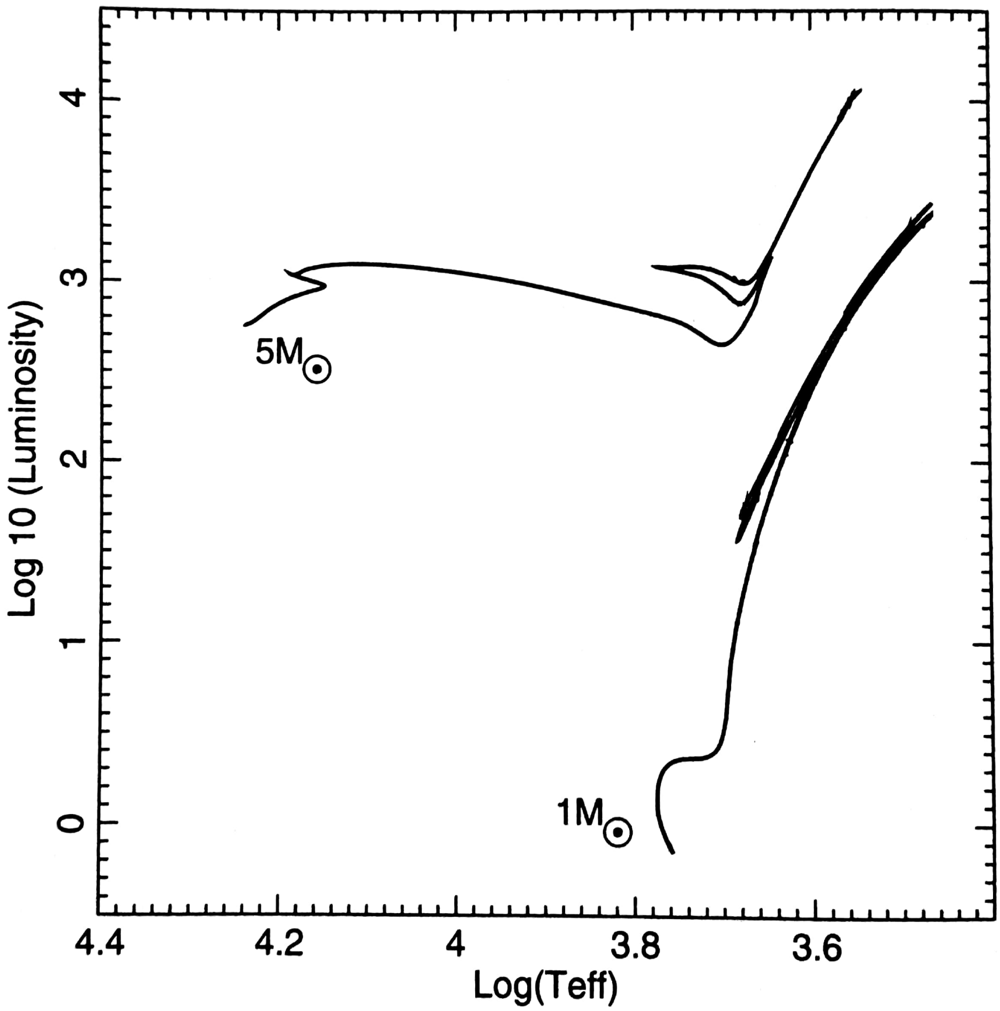

Figure 1: Hertzsprung-Russell diagram for a $1M_{\odot}$ and a $5M_{\odot}$ star of solar composition (Ref: Karakas, 2010)

3 Nucleosynthesis and Evoltion prior to AGB

All stars, including my topic of interest- the low and intermediate mass stars begin their nuclear-burning life on the main sequence, burning hydrogen to helium in their cores. For ease of study, $1M_{\odot}$ star is taken as the representative for lower mass stars ($0.8M_{\odot} \sim 2.25M_{\odot}$) and $5M_{\odot}$ star for intermediate mass stars ($2.25M_{\odot} \sim 8M_{\odot}$)
Main differences between these two stars are that the $1M_{\odot}$ go through the core helium flash and do not experience the second dredge-up and the $5M_{\odot}$ star do experience the second dredge-up.

Theoretical evolutionary tracks of a $1M_{\odot}$ and $5M_{\odot}$ star on a HR diagram are shown in Figure 1. It is clear that the $5M_{\odot}$ is much brighter on the main sequence than the $1M_{\odot}$ star by almost three orders of magnitude. Also, $1M_{\odot}$ red-giant star is cooler ($T_{eff} \approx 3,100K$) than the $5M_{\odot}$ ($\sim 4,500K$), although it has a similar luminosity ($log_{10}\frac{L}{L_{\odot}} \approx 3.2$). The luminosity of the $5M_{\odot}$ is much higher during the AGB phase.

3.1 $1M_\odot$ stars

3.1.1 Main sequence

Figure 2 shows a schematic HR diagram for a $1M_\odot$ star. During main sequence stars fuse hydrogen atoms to form helium atoms in their cores, with the central temperature and density increasing with the mean molecular weight (points 1-3). About 90% of the stars in the universe, including the sun, are main sequence stars. The temperature during core H burning is $\approx 15 \times 10^6$K, which means that the main energy generation reactions are the proton-proton (p-p) chains. The reaction is as follows.

$$^1H +^1 H- >^2 H + e^+ + \mu \tag{1}$$

$$^2H +^1 H- >^3 He + \gamma \tag{2}$$

These two steps repeat to produce another ^3He. Then the two ^3He fuse to produce ^4He.

$$^3He +^3 He- >^4 He +^1 H +^1 H \tag{3}$$

This is PPI chain and contributes 86% of the total energy of the sun. Further,

$$^3He +^4 He- >^7 Be + \gamma \tag{4}$$

$$^7Be + e^- - >^7 Li + \gamma \tag{5}$$

$$^7Li +^1 H- >^4 He +^4 He \tag{6}$$

This is PPII chain and contributes 14% solar energy. The PPIII chain produces a mere 0.07% of total solar energy and is as follows.

$$^3He +^4 He- >^7 Be + \gamma \tag{7}$$

$$^7Be +^1 H- >^8 B + \gamma \tag{8}$$

$$^8B- >^8 Be + e^+ + \gamma \tag{9}$$

$$^8Be- >^4 He +^4 He \tag{10}$$

The net reaction is:

$$4^1H- > 4^1H + 1e^+ + 1\mu + energy \tag{11}$$

This ^4He produced is deposited at the centre of the core. At one point of time H in the core gets exhausted and the star leaves main-sequence. Lifetime in the main-sequence is determined by Schonberg-Chandrasekhar limit according to which M-S terminates once the core mass reaches 10-15% of its initial mass.

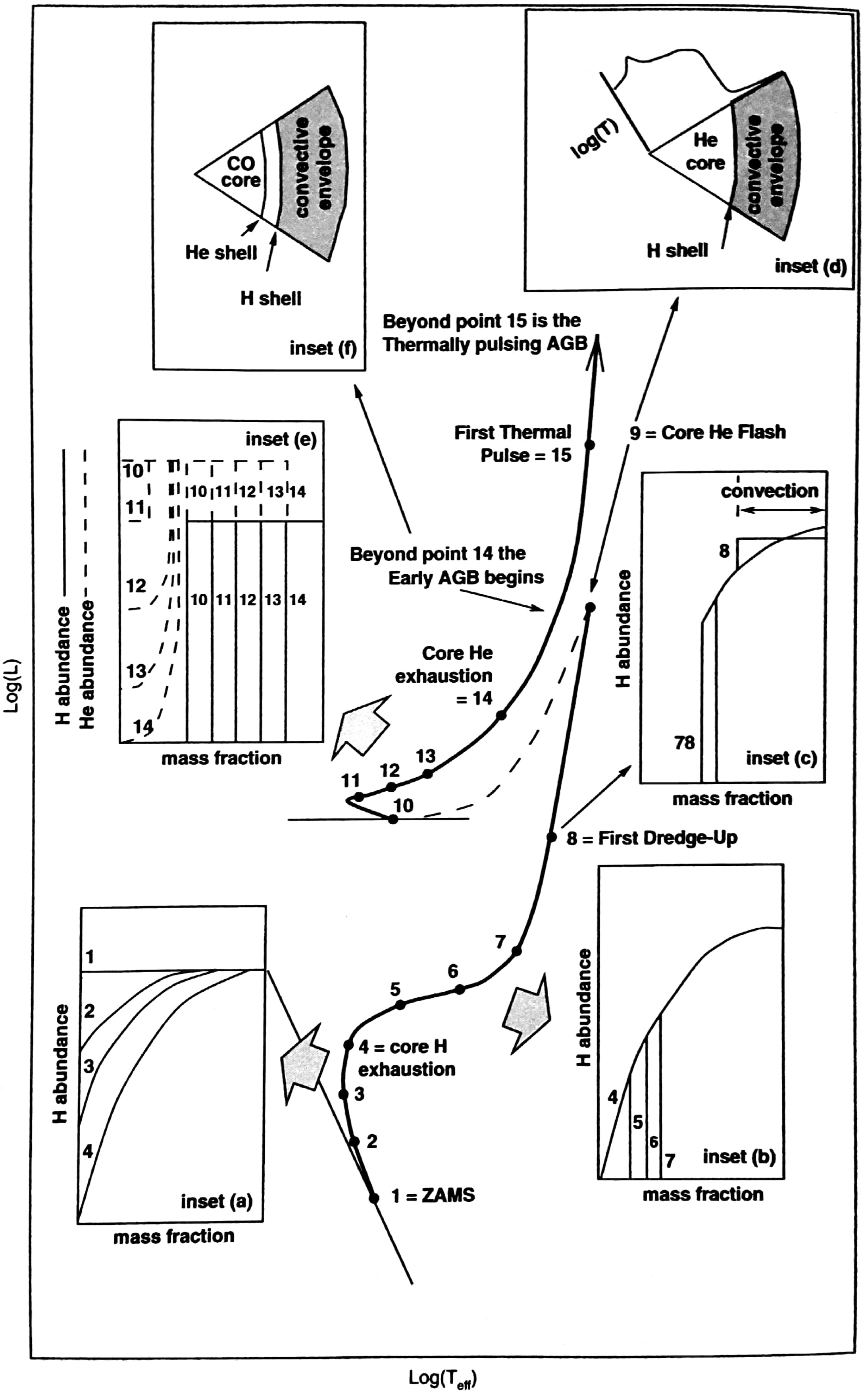

Figure 2: Hertzsprung-Russell diagram for a $1M_{\odot}$ star of solar composition (Ref: Karakas, 2010)

3.1.2 First giant branch

Following the main-sequence the star enters first giant branch and spends about 2.6 billion years. Thus it is the second most populated branch in the HR diagram. Now the star has a central He core and an outer H shell. The star first crosses the Hertzsprung gap (points 5-7) and core starts contracting and convection starts. As a result H shell starts burning stronger than before causing expansion of outer layers. This results in a drop in effective temperature. Once the star reaches Hayashi limit (point 7), its photospheric opacity has reached the maximum value and the star becomes fully convective. This enables greater luminosity to be carried away by the outer layers and temperature becomes almost constant. It is to be noted that during this phase, the effective temperature of the star depends only on H shell burning.

After crossing Hayashi limit the star moves vertically up. As core collapses further, density of the H shell increases leading to higher fusion efficiency and luminosity. Star becomes very big ($\sim$ 200 times the radius on the main sequence) but most of the mass resides in the core. Due to this reason, the outer layers are very weakly held and an FGB star loses about 30% of its mass. During the star's ascend of the giant branch, the convective envelope moves inward, mixing the outer layers with internal matter that has experienced partial H-burning. This mixing event is known as the first dredge-up (FDU). A dredge-up is the penetration of the convective envelope into regions of nuclear processing and results in mixing to the surface of the nuclear burning products (Lattanzio, 1992 [?]). It drastically affects the surface composition of low to intermediate mass stars. The main surface abundance changes are an increase in the ^{4}He abundance by $\sim$ 5%, a decrease in the ^{12}C abundance by about 20%, and an increase in the ^{14}N and ^{13}C abundances by 30%. ^{14}N/^{15}N ratio increases dramatically in after the FDU event and this increase can be attributed to the production of ^{14}N at the expense of ^{12}C and reduction in the abundance of ^{15}N from CNO cycling. Oxygen isotopes experience only small changes. Surface ratios of ^{17}O increases, ^{18}O decreases and ^{16}O remains unchanged after FDU.

First giant branch ends when the core becomes e^- degenerate. By then the star would have achieved the 100 million K required for He ignition. At this temperature the triple alpha reactions are ignited at the point of maximum temperature. The temperature and density are essentially decoupled and this leads to a violent helium ignition that is referred to as the core helium flash (point 9). During a core helium flash which lasts only a few seconds, the surface luminosity does not change greatly but the helium luminosity may reach up to $10L_\odot$ (similar to the total luminosity of a small galaxy) during the first flash. Almost 3% of ^{4}He is converted to ^{12}C during this core helium flash.

3.1.3 Horizontal branch

Following the core helium flash, the star shrinks in size and settles in the Horizontal Branch (points 10-13), where it burns ^{4}He in a convective core and hydrogen in a shell. The core has expanded and become non-degenerate. Now there are two sources of energy. 1) Core He burning 2) H shell burning. But the H shell burning is much weaker than before resulting in a reduced luminosity.

At the core ^{4}He gets converted into ^{12}C in a reaction called triple α process.

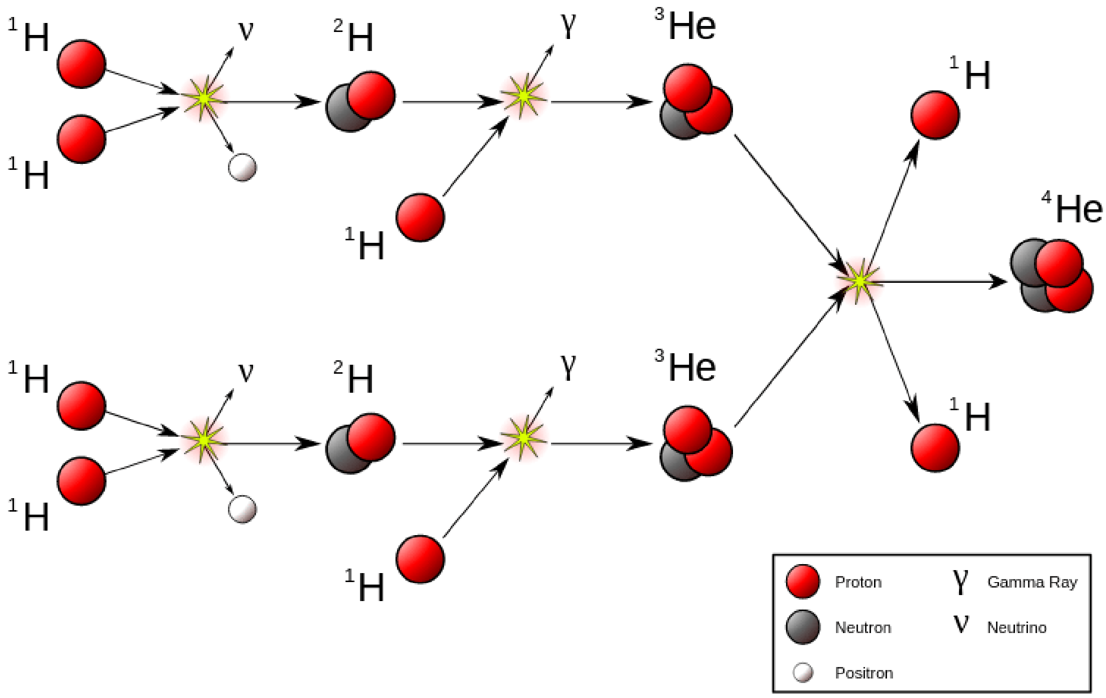

Figure 3: PPI chain reaction (Ref: Wikipedia)

$$^4He +^4 He- >^8 Be \tag{12}$$

This ^{8}Be is very unstable (life time $\approx 10^{-16}$ sec.).

$$^8Be +^4 He- >^{12} C + \gamma \tag{13}$$

This collision between Be and He happens only if temperature $\approx 10^8$ K, or else Be decays. One half of the C produced will capture another He to produce ^{16}O.

The coulomb repulsion is larger for He than for H, hence more energy is required by the triple alpha process to maintain the star in hydrostatic equilibrium. Also the energy produced during the triple α process is less as compared to that produced during main sequence phase. Thus the star spends only $\sim$ 100 million years (myr) in the horizontal branch.

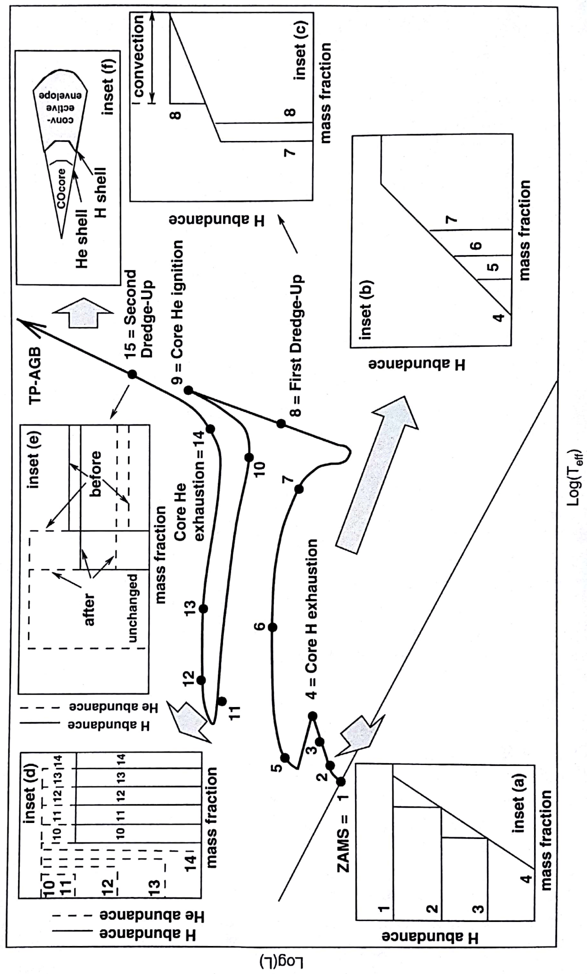

Figure 4: Hertzsprung-Russell diagram for a $5M_{\odot}$ star of solar composition (Ref: Karakas, 2010)

3.2 $5M_{\odot}$ stars

Figure 4 shows a schematic HR diagram for a $5M_{\odot}$ star.

3.2.1 Main sequence

Main sequence phase of a $5M_\odot$ star is almost similar to that of its $1M_\odot$ counterpart, but here the main reaction converting hydrogen to helium is carbon-nitrogen-oxygen (CNO) cycle. The main-sequence evolution of the $5M_\odot$ star corresponds to points 1-4 in Figure 4. The high temperature ($\sim 15 \times 10^{17}$ K) causes convection in the core. The CNO chain is as follows.

$$^{12}C + p- >^{13} N + \gamma \tag{14}$$

$$^{13}N- >^{13} C + e^{+} + \mu \tag{15}$$

$$^{13}C + p- >^{14} N + \gamma \tag{16}$$

$$^{14}N + p- >^{15} O + \gamma \tag{17}$$

$$^{15}O- >^{15} N + e^{+} + \mu \tag{18}$$

$$^{15}N + p- >^{12} C + \alpha \tag{19}$$

The net reaction is:

$$4p- > \alpha + 2e^{+} + 2\mu + energy \tag{20}$$

Following core H exhaustion, the star moves to the first giant branch.

3.2.2 First giant branch

This phase is almost similar to that in a $1M_\odot$ star. Now there is a ^{4}He core and a burning ^{1}H outer shell. The core contracts and outer envelope expands. Star crosses Hertzsprung gap (5-7), reaches Hayashi limit and then climbs vertically up the branch. First dredge-up happens during the ascend (point 8) and the convection reaches interior where partial H burning occurred during main sequence phase. As a result products of the CN burning, ^{14}N and ^{13}C are mixed to the surface. But the depth of this first dredge-up relative to the total mass of the star is less as compared to $1M_\odot$ stars. Unlike the low mass stars, here the contracting core do not become e$^-$ degenerate. But acquires enough energy for central He burning and enters horizontal branch.

3.2.3 Horizontal branch

This period of central He-burning lasts about 20 Myrs. The core He-burning timescale is much shorter than the 90 Myrs spent on the main sequence but longer than the 3 Myrs spent on FGB. This is one of the major difference between a low mass and intermediate mass star. Now there are two sources of energy, central He burning and the outer H shell burning. The central He burning proceeds exactly as mentioned in the case of $1M_\odot$ star. Following core He exhaustion, the star ascends the AGB. Unlike low mass stars,

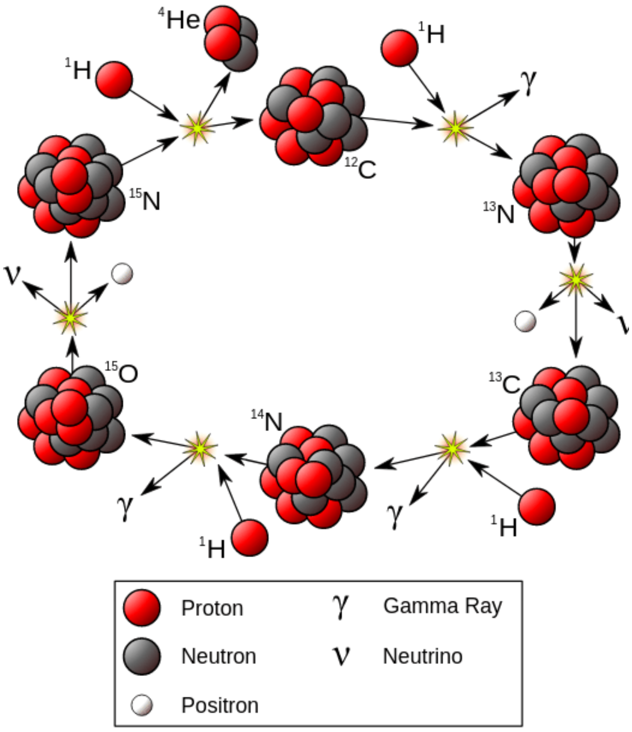

Figure 5: CNO cycle (Ref: Wikipedia)

intermediate stars experience a strong second dredge-up on this branch. The changes in surface abundances for different elements are almost similar to that in a $1M_{\odot}$ star.

4 Asymptotic giant branch

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AGB is the last nuclear burning phase of evolution for low and intermediate mass stars. Stars spend only about 1% of their main-sequence life time on this branch. AGB stars are the factories for production of many elements (including many heavy metals) in the universe. One-third of carbon in milky way galaxy is produced by AGB stars. The study of AGB stars helps in understanding the contribution of low and intermediate mass stars to the chemical evolution of galaxies and stellar system. The AGB is divided into:

1) Early AGB (E-AGB)
2) Thermally Pulsing AGB (TP-AGB)

4.1 Early AGB phase

After central He exhaustion, C-O core starts contracting under gravity. The outer layers expand and cool like it was during the FGB phase. Due to the expansion of H shell and He rich zone, temperature of H shell shows a considerable decline. In a star having mass less than $4M_{\odot}$, the H shell burns with a very low intensity. If the mass of star is greater than $4M_{\odot}$, then the H shell gets completely extinguished. Now, only the He burning shell contributes to expansion as well as luminosity of the star. The temperature is almost constant during this ascend and this is evident from the HR diagram. He burning shell adds more mass to the growing C-O core and expansion continues in the outer layers.

The convective zone moves interior till the composition discontinuity left behind by extinct H shell. This inward movement of convective zone is defended by the H shell which is still active at very low intensity in $<4M_{\odot}$ stars. But in higher mass ($>4M_{\odot}$) stars, this convective action leads to the second dredge-up (SDU). Convective layers penetrate down to He rich regions as a result of which ^{4}He, ^{12}C and ^{14}N reach outer layer. Another important consequence of the second dredge up is that it reduces the mass of the H exhausted core.

4.2 Thermally pulsing AGB (TP-AGB)

He burning shell expands and approaches H-He discontinuity. Its luminosity decreases and becomes thinner as it runs out of fuel. Thus the layer above it starts contracting. In response the H shell gets heated and is re-ignited. Now there are two shells burning with different pace. H shell adds more mass to the inter-shell region (He rich region). This increases the temperature and pressure at the junction between inter-shell region and He burning shell. When the mass of inter-shell region reaches a critical value, He shell starts burning in an unstable manner (due to the reduced size of shell) giving rise to a thermo-nuclear run-away called He shell flash. It is to be noted that this He flash is different from the core He flash. This flash continues for several hundred years and reaches $\sim 10^{8}L_{\odot}$ within the first year. The flash drives convection in inter-shell region called the intershell convection zone (ICZ). ^{12}C produced during 3α process and other elements produced during He burning are mixed throughout the ICZ. The He flash do not increases luminosity of the star, instead causes the expansion of the intershell region. As a result He shell also expands, cools and gradually the He shell flash dies out. This

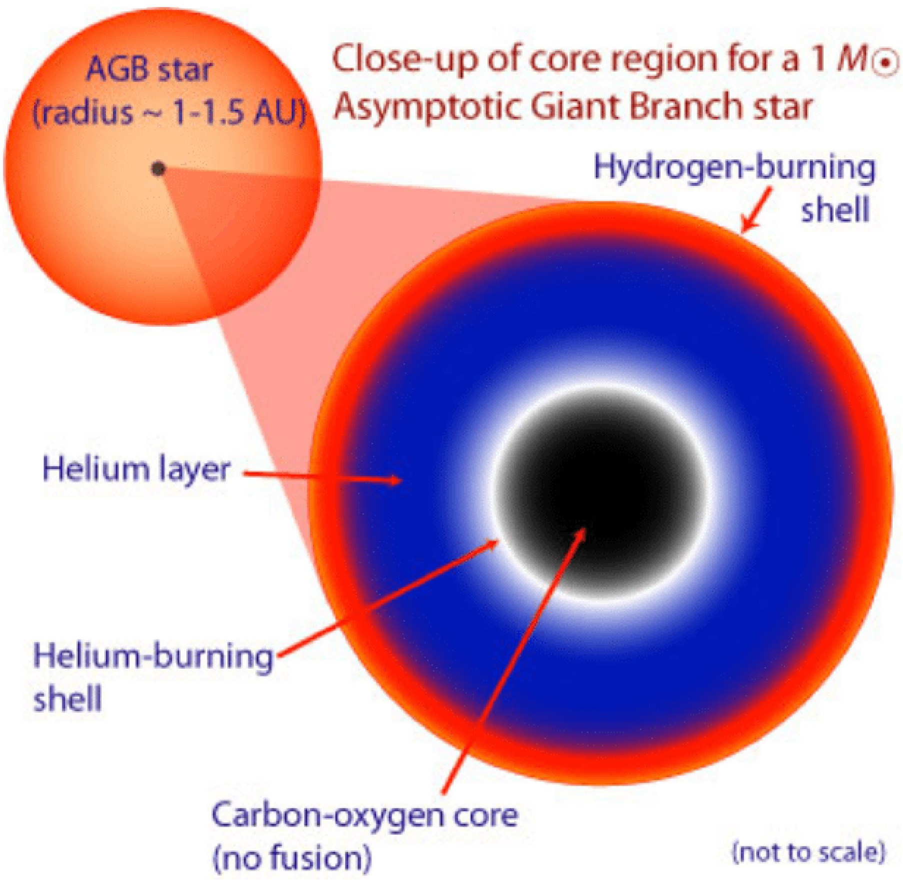

Figure 6: Schematic structure of a solar mass star during the AGB phase (Ref: Steidel et al., 1996)

is followed by stable He burning for a few hundred years. The expansion and cooling of ICZ extinguishes the H shell.

This also aids the deeper penetration of outer convective envelope. Sometimes the penetration reaches the interior of now extinct H burning shell. This is the third dredge-up. TDU limits the core mass growth and efficient TDU implies a more efficient nucleosynthesis. He and products like ^{12}C reach the surface as a result. After TDU, H shell is reignited and remains active for many years. During this whole time He shell is inactive. H shell burning starts adding mass to the intershell region and the whole process repeats. Thus this phase is characterized by long period quiescent H shell burning-inter pulse state interrupted by thermal pulses.

The TDU and thermal pulses mixes ^{12}C to the surface. And if the surface C/O ratio increases above 1, then the star is called a carbon star. The TP-AGB phase is also characterised by luminsosity variability arising from pulses and the surrounding dust clouds.

5 Nucleosynthesis during AGB

Though low and intermediate mass stars spend very short time on TP-AGB, it is where the richest nucleosynthesis occurs. It is caused by instability of He shell leading to TP & TDU. The third dredge-up is very important process; it mixes the products of He burning to the star surface. Also, He shell products are transported to H shell during TDU. There they undergo proton capture during interpulse period. Thus nucleosynthesis happens during the dredge-up and also during interpulse period. Another process called hot bottom burning (HBB) also happens about the same time contributing to the nucleosynthesis.

5.1 Nucleosynthesis in H burning shell

The nucleosynthesis in hydrogen burning shell is primarily caused by CNO cycle, but then Ne-Na chain and Mg-Al chain also operate there aiding the process.

5.1.1 CNO cycle

^{4}He is the main product of CNO cycle. The abundances of ^{13}C and ^{14}N also increases. They are produced in the expense of ^{12}C and ^{15}N during the CN cycle. Later the ^{18}O and ^{16}O are converted to ^{14}N during the NO cycle resulting in an increase in its abundance. CN cycle is more active than NO cycle when the temperature of the star is around 20 million K. But for higher temperature (T $>$ 30 million K) NO cycle becomes the most prominent reaction. ^{17}O also shows an increase during the CNO cycle, but it depends largely on the uncertainity of ^{17}O + p reaction.

5.1.2 Ne-Na chain

During an Ne-Na chain reaction, the abundance of ^{22}Ne decreases coniderably as it gets converted to ^{23}Na at about T $\approx$ 20 million K. Thus the main result is the increase in abundance of ^{23}Na. The dominant ^{20}Ne is not extensively altered by means of H-shell burning. But at T $>$ 80 million K, the ^{23}Na is destroyed to produce ^{20}Na and this slightly enhances the ^{20}Ne abundance.

5.1.3 Mg-Al chain

The Mg-Al chain starts operating at about T $\approx$ 30 million K. The abundance of ^{24}Mg remains unaltered because only when the T $>$ 70 million K, the ^{24}Mg takes part in the reaction. Quantity of ^{25}Mg reduces as it is burnt to ^{26}Al. This ^{26}Al either undergoes a β decay to produce ^{26}Mg or else may capture a proton first and become a ^{27}Si. This ^{27}Si then β decay to form ^{27}Al. The abundance of ^{26}Mg is also high as its conversion to ^{27}Al occurs only when T $>$ 60 million K. Overall, the abundance of ^{26}Mg increases, ^{25}Mg decreases and ^{24}Mg remains unaltered.

Products produced in H shell may not reach the outer shell. They are again processed through He shell. Only those elements that remains unaltered reaches the surface. Most of the H shell products thus do not reach the surface including ^{14}N and ^{26}Al. ^{17}O and

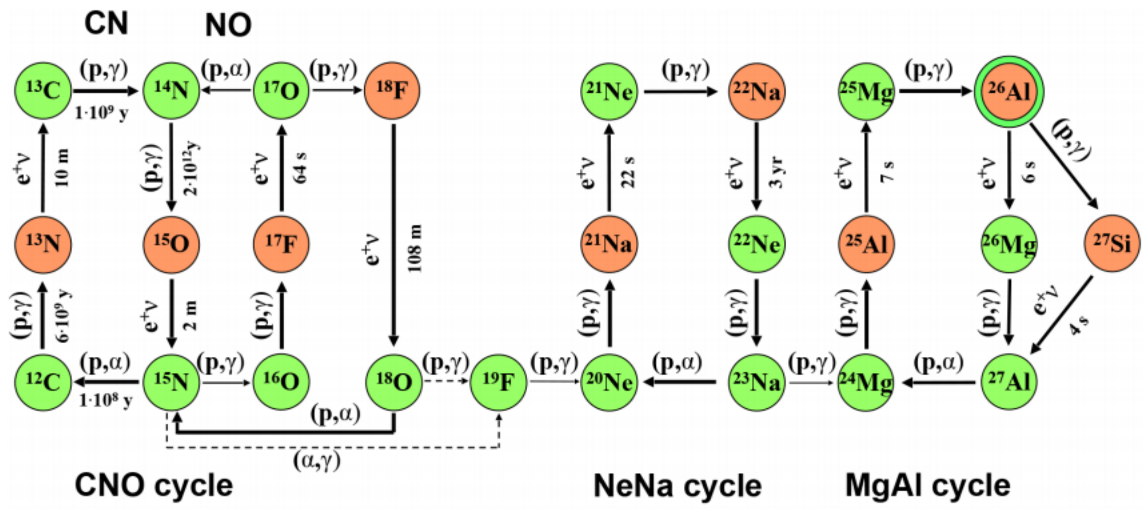

Figure 7: Reaction cycle of CNO, NeNa, and MgAl cycles. Stable radioactive nuclei are shown in green, while short lived are shown in orange. ^{26}Al is long lived nuclide in its ground state, while its metastable state decays directly to ^{26}Mg with a short half-life. (Ref: Boeltzig et al., 2016)

^{23}Na are the two major products that manage to reach the outer envelope of the star.

5.1.4 Slow neutron capture process (s-process)

It has been evident from spectroscopic observations that many AGB stars are enriched in elements that are heavier than iron like Zr, Y, Sr, Ba, La, Pb, Nb, Mo etc. These elements are formed by a process called slow neutron capture on ^{56}Fe nuclei. Heavier elements are not produced by normal nucleosynthesis because of the large electrostatic force of repulsion they possess. Thus no proton or α capture happens. This high electrostatic repulsive force is a direct result of their high proton number.

S-process is slow compared to β decay and it happens only when the neutron density is low ($N_n \sim 10^7$ neutrons/cm^3). Another interesting fact to be noted is that, if we look at solar abundance distribution, those nuclei/elements with magic number of neutrons (n = 2, 8, 20, 28...50, 80, 82,126) occupy the peaks. Those elements whose both proton and neutron number are magic numbers are stable against neutron capture (eg.: ^{16}O). S-process require a constant supply of free neutrons as they are unstable and decay in $\approx$ 10 minutes. This is provided by Ne-Mg chain in massive AGB stars ($> 4M_\odot$) and C-O chain in lower mass stars ($< 4M_\odot$).

5.2 Nucleosynthesis during thermal pulses

Thermal pulses occurs in the intershell region which are primarily composed of 98% ^{4}He and 2% ^{14}N. The nucleosynthesis in this region is driven by two reactions:

1) Triple α process which converts 3 ^{4}He into ^{12}C during shell He flash.

2) $^{12}C^{16}O$ cycle which is particularly unimportant during thermal pulses because of the short He-burning timescale.

After He flash, the entire composition of the He shell changes owing to the triple α process. Now the shell is composed of 70-75% ^4He and 20-25% ^{12}C. This is one of the most important C producing reaction for a low and intermediate mass stars. It is to be noted that AGB stars are important source of carbon. They produce about one-third of total C in galaxy. Low metallicity stars have a higher C/O ratio due to less oxygen content and an efficient second dredge-up. In the intershell region, small amounts of ^{16}O, ^{22}Ne and traces of ^{17}O, ^{23}Na, ^{25}Mg, ^{26}Mg and ^{19}F are also found. The exact composition of various elements depends on several factors like mass and composition of stars before pulses, duration of He flash, peak temperature at which burning happens etc. All these factors vary from one star to another depending on mass and metallicity of the star and they change as the star moves through TP-AGB branch.

As mentioned above CO cycle is not active enough to produce much oxygen. Thus the composition of $^{16}O \approx 1\%$ in the intershell region. Another element produced in the intershell region is ^{22}Ne. At first ^{14}N is converted into ^{18}F which then decaysa β particle to produce ^{18}O. This O absorbs an α particle to become neon. The composition of $^{22}Ne \approx 2\%$ in the intershell region, which is fairly high. The temperature during thermal pulses exceeds 300×10^6K in high mass stars ($> 4M_\odot$). ^{25}Mg and ^{26}Mg are produced in them from $^{22}Ne(\alpha,n)^{25}Mg$ chain and $^{22}Ne(\alpha,\gamma)^{26}Mg$ chain. In low mass stars, this high temperature is achieved only during late AGB phase. And hence the $^{22}Ne(\alpha,n)^{25}Mg$ chain is only marginally activated in them. This reaction is particularly critical as it produces loose neutrons that may be captured by iron-peak elements during the s-process.

5.3 Hot bottom burning

In intermediate mass stars ($> 4M_\odot$) the bottom of the convective envelope can dip into the top of the H-burning shell, inflicting proton-capture nucleosynthesis to occur there at high temperature ($> 3 \times 10^7$K). This greatly influences the surface composition of the stars and also increases surface luminosity by breaking core mass-luminosity relation. This phenomenon is called hot bottom burning. During HBB process CNO cycle, Ne-Na cycle and Mg-Al cycle operate if the envelope is sufficiently hot. The conversion of ^{12}C into ^{14}N is very efficient during HBB and this reaction prevents the formation of carbon stars by keeping the C/O ratio below unity. Another important element produced is Li via the Cameron Fowler mechanism (PP II chain)in cooler regions of the star. This lithium produced may further capture a proton and get destroyed. But it is still in doubt whether AGB stars contribute to galactic enrichment as Li is usually destroyed before it is expelled. .^{19}F abundance reduces during FO cycle and that of ^{26}Al increases as it is produced when temperature reaches 90 million K.

5.4 AGB star yields

Stellar yield is the amount (in mass) of species 'i'that is expelled to the interstellar medium over the course of a star's life.

$$M_i = \int_0^T [x(i) - x_0(i)] \frac{dM}{dt} dt \tag{21}$$

where,
M_i = yield of species 'i'(in solar masses).
$\frac{dM}{dt}$ = current mass loss rate
$x(i)$ and $x_0(i)$ = current and initial mass fraction of 'i'
T = total lifetime of stellar model

M_i is positive if the element is produced and it negative when element gets destroyed. The above equation when integrated gives the total amount of species 'i 'expelled into interstellar medium.

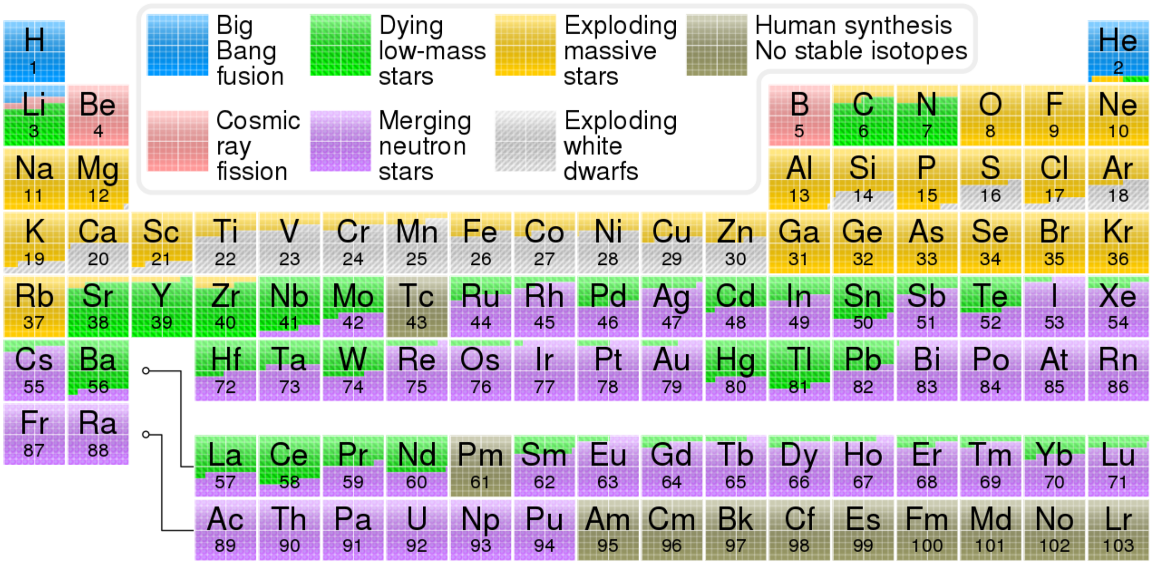

Figure 8: Periodic table showing the source of formation of different atoms (Ref: Science Alert)

6 Mass loss and termination of AGB phase

One of the characteristic feature of TP-AGB phase are the thermal pulses. The number of thermal pulses and the lifetime in TP-AGB phase is limited by:

1) decreasing mass of H rich envelope
2) increasing mass of degenerate CO core

As the mass of degenerate CO core increases, it becomes equal to Chandrasekhar mass ($M_c h \approx 1.4 M_{\odot}$). In such a condition the carbon in the core gets ignited through a carbon flash. This carbon flash is so powerful so that it can disrupt the entire star. But with observation, it has been understood that c-flash never happens in real AGB stars even for stars having mass $> 8 M_{\odot}$. That is because the mass loss is so strong that the envelope of the star gets removed before the core has grown significantly. This mass loss is caused by AGB winds driven by pulsations and radiation pressure on the surrounding dust particles. Mass loss rate increases with stellar luminosity. Thus the mass loss terminates the AGB phase and in turn determines level of chemical enrichment.

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