

THE HISTORY OF THE *S* PROCESS AND ITS PRESENT STATE

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ABSTRACT. We review the history and the present status of the *s*-process and point to problems in need of clarification. In some cases the problems have to do with lack of experimental data and in other the theory is missing.

KEYWORDS: *s*-process, element-synthesis.

1. INTRODUCTION

Slow neutron capture is one of the two main stellar processes which is believed to be responsible for the synthesis of heavier than iron (HTI) elements via neutron capture. Our review is planned as follows: First we discuss the basic idea how to overcome the Coulomb barrier at high Z elements. Then we discuss the attractiveness of neutron absorption reactions. The next question is: What is the source of neutrons? This question is associated with the stellar evolution phase, during which neutron capture takes place. Finally, we discuss how the process is supposed to work, and we examine the present state of knowledge and the suggested scenario.

2. TYPES OF NEUTRON CAPTURES

In view of the large Coulomb barrier presented by HTI nuclei, it is natural to think about neutrons as the driving force of the synthesis of these elements. An increase in temperature to a degree which allows for charged particle reactions is out of the question, because long before such reactions can take place, massive nuclei disintegrate via photo-reactions.

Successive neutron capture on an HTI nucleus leads to neutron-rich nuclei. The more neutrons the nucleus has, the greater its instability to β -decay becomes. Hence, we distinguish between two types of processes: (a) Slow neutron captures, which have a time scale of $\geq 10^6$ yr, and (b) rapid neutron captures, which have a time scale of ≤ 1 s. There is no theory, scenario or astrophysical site where an in-between neutron capture takes place. Here we discuss the first case.

How much there is to synthesize? There are 170 nuclei with $Z > 30$ per 2.8×10^{10} protons. The relative abundance of the iron group is $\text{Fe} = 9.0 \times 10^5$, $\text{Co} = 2.3 \times 10^3$, $\text{Ni} = 5.0 \times 10^4$, $\text{Cu} = 4.5 \times 10^2$, and $\text{Zn} = 1.1 \times 10^3$ (based on Grevesse and Anders [9] and Barns and Bash [9]). So we have to convert about 1.8×10^{-4} of the Fe group into HTI nuclei. If these nuclei are formed by means of neutron capture, we need at least 1.5×10^4 neutrons, which is almost one neutron per iron nucleus. So, while the energetic demands are negligible, the source of the neutron is a

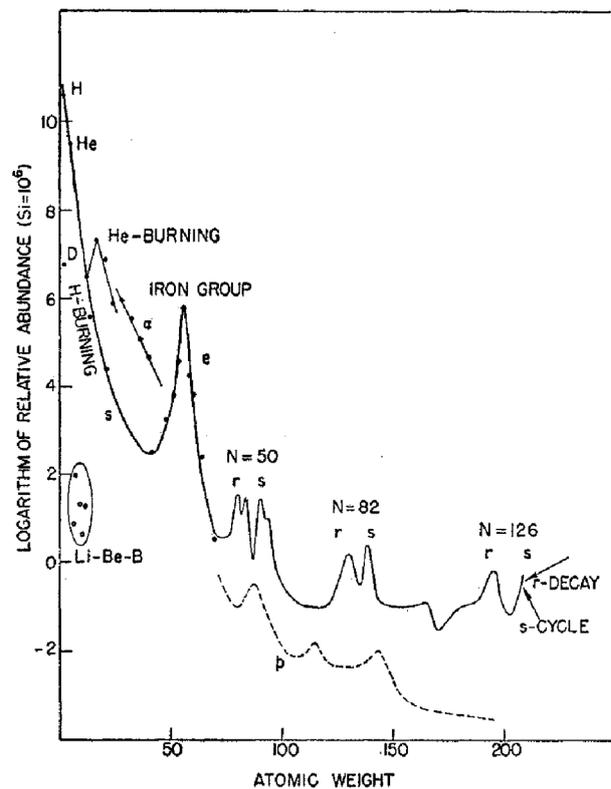


FIGURE 1. The schematic cosmic abundance curve as provided by B2FH in 1957. It shows the two abundance peaks attributed to the *r* process and the *s* process, respectively.

crucial problem. The good thing is that synthesis of the HTI nuclei is a side effect among trace elements, and has no effect on the evolution of the star.

In view of the problems that we mentioned above, we recall Mayer' and Teller's idea of fission of a super heavy nucleus as a way to obtain HTI nuclei. However, this idea is nothing but shifting the problem to what is the nature of the primordial super-heavy nucleus. Another possibility is the $\alpha\beta\gamma$ theory, which is quite successful in synthesizing HTI elements for $A > 100$.

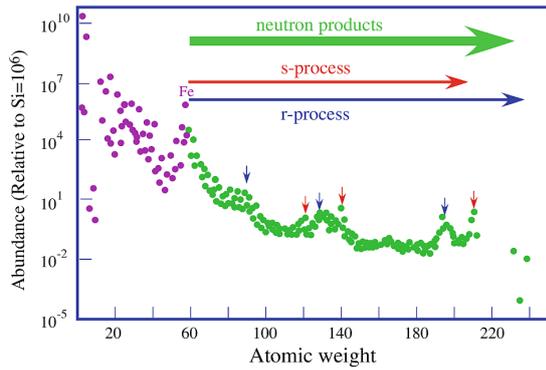


FIGURE 2. The presently assumed sources of the HTI elements.

3. WHAT TO EXPLAIN?

In Fig. 1, we show the cosmic abundance of the elements. This was the basis for the seminal paper by Burbidge, Burbidge, Fowler and Hoyle in 1957 (known as B2FH) [2]. In 1956, Suess and Urey argued that no single theory can explain all the abundances of nuclei and isotopes [31].

A summary of present day theories is shown in Fig. 2. The *s*-process can synthesize elements up to Lead, while the *r* processes contributes to the synthesis of the HTI elements, and also synthesizes the most massive known nuclei. The contribution of the two processes to the abundance of a given nucleus has to be separated, and this can be carried out only theoretically. For a general nucleus the abundance predicted by the “best” *s*-process model is calculated first and then the *r*-process contribution is found by subtraction. The “best” *s*-process is determined by the results for the elements which are known to be synthesized only by the *s*-process. Obviously the uncertainties in the theory propagate through the two thus coupled processes.

The resulting abundances are clearly a question of the behavior of the neutron capture cross-sections at thermal energies. In Fig. 3 we show the cross section for neutron capture as a function of atomic weight *A*. It is obvious that the minima in the cross section should correspond to the maxima in the abundance. Thus, the closed nuclear shell corresponds to the more abundant elements. In Fig. 4 we show the cross-section around the magic number 82.

Since the *s*-process has a time scale longer than any β -decay time, it runs along the bottom of the valley of nuclear stability, in contrast with the *r*-process, which runs through the most unstable nuclei, namely, along the neutron drip line (see Fig. 5).

Slow neutron capture continues until the nucleus become unstable against α -decay, which has a time scale shorter than about $\sim 10^6$ yr. Hence the process cannot synthesize elements beyond Lead. The last reaction is $^{209}\text{Bi} + n \rightarrow ^{210}\text{Bi} + \alpha$.

If we assume a steady state, it is simple to solve analytically for the abundances, because in a steady

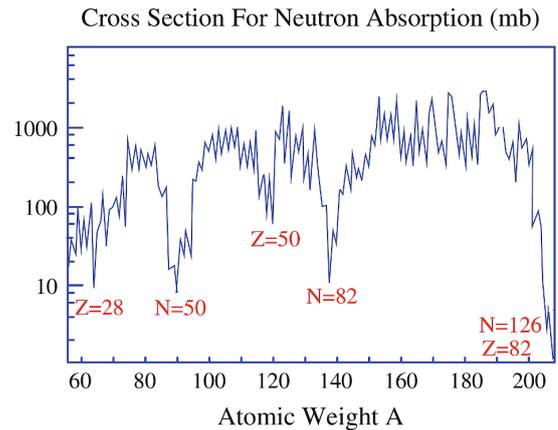


FIGURE 3. The cross-section of neutron capture as a function of atomic weight

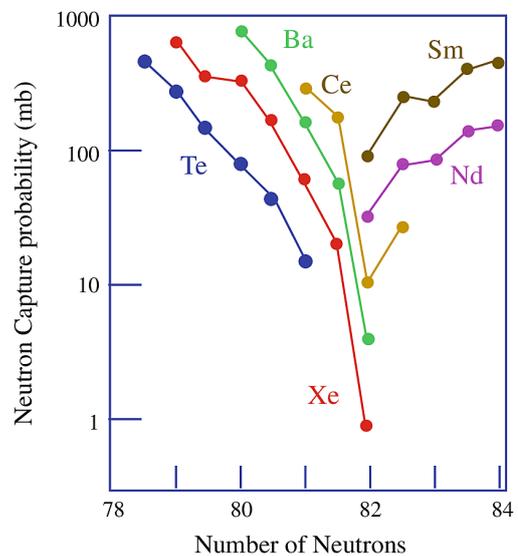


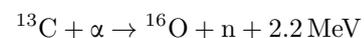
FIGURE 4. The cross-section of neutron capture as a function of neutron number in the nucleus.

state $N\sigma = \text{const}$. In Fig. 6 we show the product $N\sigma$ for the first HTI elements. It is clear that the steady flow assumption is not good.

Consequently, Seeger et al. [30] suggested time-dependent irradiation and the first assumed arbitrary irradiation of the form $ne^{-t/\tau}$, where τ is a free parameter. The results are shown in Fig. 7. The improvement in the fit is obvious.

4. NEUTRON SOURCES

Greenstein, who was an astronomer and not a nuclear physicist, and also independently Cameron, realized that the exothermic reaction



is good stellar neutron source. Indeed, this reaction is the most important and most famous neutron source for synthesizing nuclei in the *s*-process. B2FH added

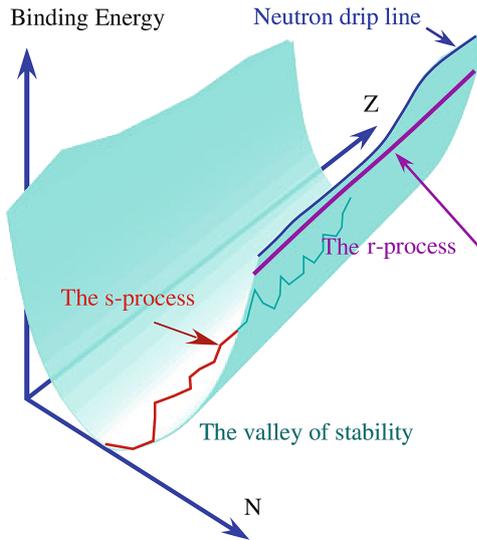


FIGURE 5. The valley of nuclear stability and the path of the *s* process and the *r* process.

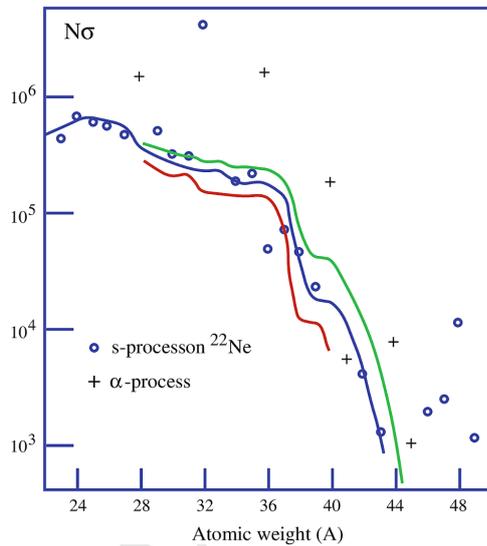
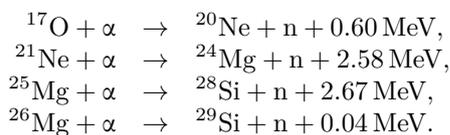


FIGURE 6. The product (according to B2FH) of the abundance times the cross-section.

the following exothermic reactions:



The next reactions in this series are endothermic, namely, the reactions need energy to proceed,



Most of the seed nuclei are rare, so that large changes in abundances are expected. If the source operates during He burning, there will be plenty of α -particles, else you call for photoionization of α -nuclei.

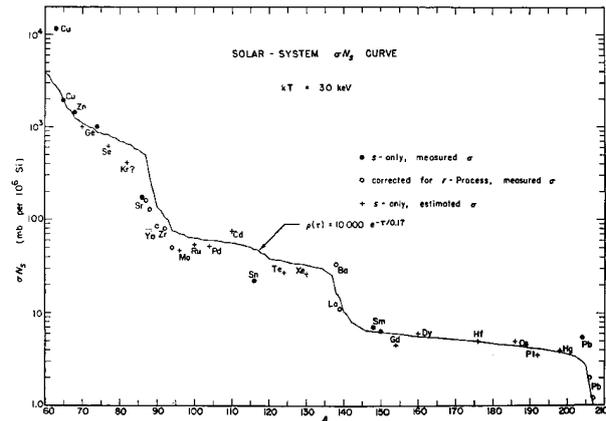


FIGURE 7. The solid line is a calculated curve corresponding to an exponential distribution of the integrated neutron flux. After Seeger et al. [30].

The targets of the α particles in the generation of the neutrons are outside the main stream of synthesized nuclei. This fact is of fundamental importance, because it allowed us to model the *s*-process without attaching it to a specific stellar model. The stellar model does affect the *s*-process, but the *s*-process has no effect on the structure or the evolution of the star. It deals with trace elements and minute energy consumption. The targets are rather rare species, and hence they can provide only limited numbers of neutrons. If the scarcity of neutrons is not a sufficient worry for the theoreticians, another problem is the existence of a large amount of ${}^{14}\text{N}$ which, for our purposes here, is a neutron poison via the reaction ${}^{14}\text{N} + n \rightarrow {}^{14}\text{C} + p \rightarrow {}^{14}\text{N} + \beta^-$.

5. HOW TO SQUARE THE CIRCLE?

Fowler, Burbidge and Burbidge [2] (in 1955), and later B2FH, reiterated the supposition that: During the critical phase in which neutrons are released, the product of the 3α reaction, ${}^{12}\text{C}$, which should be abundant, mixes with the envelope, and the mixing brings fresh hydrogen-rich material into the burning zone. Consequently, the hydrogen interacts with the ${}^{12}\text{C}$ and converts it to ${}^{13}\text{N}$, which decays into ${}^{13}\text{C}$, and which is then available for additional absorption of an α and the release of neutrons.

Simple mixing is out of question, as it completely ignores that outside the region in which He burns into carbon, there is a region in which hydrogen burns into helium. And if the outside envelope mixes with the helium burnt material it will wash away the entire structure of the red giant.

B2FH therefore hypothesized, that *sporadic mixing* between the burning zone and the unburnt envelope leads to a continuous supply, not too much but just in measure, of the raw materials needed for the production of neutrons. Moreover, at the same time, ${}^{12}\text{C}$ is dredged up by the same hypothesized mixing from the burning zone into the envelope and creates a

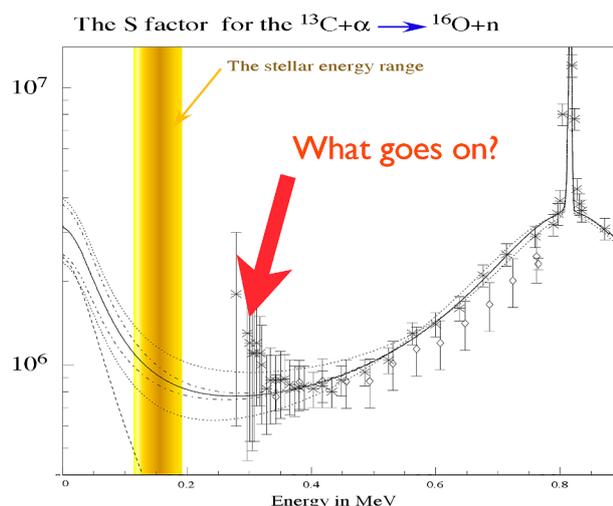


FIGURE 8. The measured range and the required range $^{13}\text{C} + \alpha \rightarrow ^{16}\text{O} + n$ (after Johnson et al. [12]).

star with a surface rich in carbon, known as a carbon star. Thus, the known “carbon stars” should be, a λ B2FH, the location where neutrons are released and build HTI nuclei. B2FH did not calculate a stellar model in which the mixing mechanism operates, nor did they propose any specific sporadic mixing mechanism. It was just a scenario. It should be noted that, back in 1954, while suggesting the ^{13}C reaction, Cameron already realized the problem with the supply of neutrons. Cameron therefore stated, that the ^{13}C reaction is particularly important in those stars with appreciable internal circulation. However, the circulation, the timescales, the mechanism, etc., were not specified.

6. MERRILL’S DISCOVERY

In 1952, Merrill discovered technetium (^{98}Tc) in S type stars, namely in a late-type giant star whose spectrum displays *s*-process elements, e.g. zirconium and yttrium. Technetium is radioactive, with a half lifetime of 4.2×10^6 yr, which is much shorter than the lifetime of the star. Hence it must have been produced recently inside the star, and brought up to the surface. Thus, it provides evidence that “some mixing” between the internal furnace and the envelope takes place. The title of Merrill’s paper was *Spectroscopic Observations of Stars of Class S*. The boring title that Merrill chose for his paper conceal a great discovery. In present-day practice, the title might have been *At long last: The first-ever discovery and proof of nuclear reactions in stars*.

7. THE NEUTRON SOURCE PROBLEM

There are two basic problems with the neutron source. The first problem has to do with the nuclear data, and the second has to do with the stellar power of the neutron source. In Fig. 7 we show a typical case, where the measurements are made at excessively high

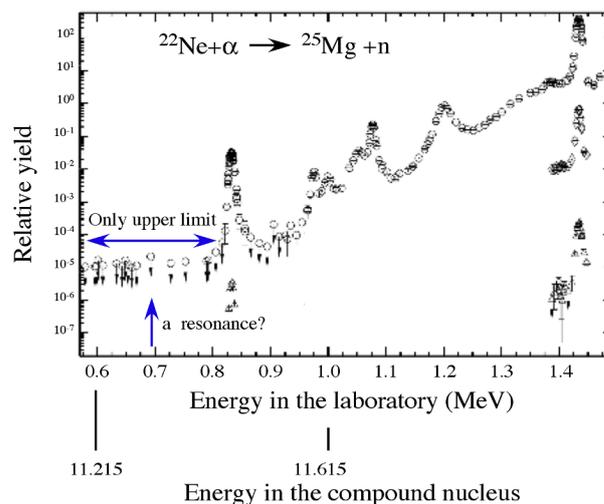
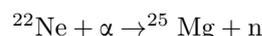


FIGURE 9. The measured range and the required range $^{22}\text{Ne} + \alpha \rightarrow ^{25}\text{Mg} + n$. This reaction was assumed to take place in stars more massive than $4M_{\odot}$ (after Jaeger et al. [11]).

energy, and extrapolation to lower energies is required. The extrapolation is sometimes over a small energy range, so the extrapolation is reliable. However, in many cases the extrapolation is over a too large a range, and/or the measured cross-section varies in such a way as to defeat any extrapolation.

In Fig. 8 we show a bad case. The cross section oscillates in a way that would turn any extrapolation questionable.

A similar case is shown in Fig. 9, where the experimental results are shown for the



reaction. This reaction was suggested by Cameron [4]. Clearly, the situation is not good and it is obvious that extrapolation can yield almost any result.

The second problem of the intensity of the neutron source was ‘solved’ by sporadic mixing, which refreshes the source periodically.

8. A ROSETTA STONE: FG SAGITTAE

In 1960, Richter [22] reported that the star FG Sagittae had changed its luminosity by a factor of about 50 since the beginning of the twentieth century, on top of which smaller luminosity variations had been observed. Richter gave no information about anything unusual with respect to *s*-process elements.

Between 1960 and 1967, the spectra of the star were investigated by Herbig and Boyarchuck, who found that the spectra changed during the 7 years of observations from B8 Ia to A5 Ia, which indicates cooling. A dramatic change took place when Langer, Kraft and Anderson discovered in 1974 [13] that the spectral lines of several *s*-process elements had begun to appear in the spectra of FG Sagittae some time in 1967, and since then they had increased their strength

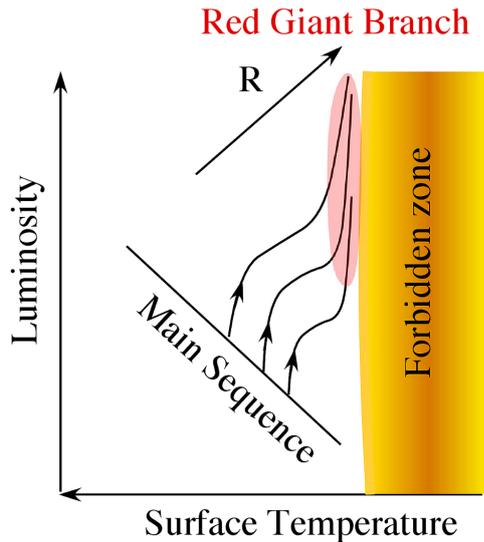


FIGURE 10. The tip of the Red-Giant where the helium flash takes place. The first suggested location for the *s*-process.

with time, to the point that their present day values are about 25 times the solar value. Kraft, taken aback by the phenomenon, named the star as the Rosetta stone of nucleosynthesis. Further observations revealed that FG Sagittae ejected a planetary nebula some 6000 years ago. In 1977, Kipper and Kipper [17] found that while the abundances of the *s*-process elements had changed, the abundances of the iron peak elements had remained unchanged. In the past 100 years, FG Sagittae brightened by a factor of more than 70 and then cooled off at a rate of 340 K/yr between 1955 and 1965, and at a rate of 250 K/yr between 1969 and 1974.

The full story of FG Sagittae has not yet been revealed [32], but the accepted view at the present time is that FG Sagittae experienced the last episode of *s*-process elements formation during the “last thermal pulse” and ejected the rest of the envelope as a planetary nebula.

9. THE ASTROPHYSICAL SITE

The first ideas were that the *s*-process takes place during the helium flash (see Fig. 10). However, various calculations of the He-flash indicated that the flash is not sufficiently strong to cause mixing between the core and the envelope, and the idea was dropped.

After the helium flash, the star retreats from the tip of the Red-Giant branch and ignites He in the core. As the helium in the cores is exhausted, the star again moves towards the tip of the Red Giant. When the helium is exhausted in the core, the star produces energy in the shell around a carbon–oxygen core (cf. Fig. 11). But then the H-shell is way out.

The phase of two burning shells is unstable, and the instability expresses itself in the form of “thermal oscillations”. The extreme sensitivity of the nuclear

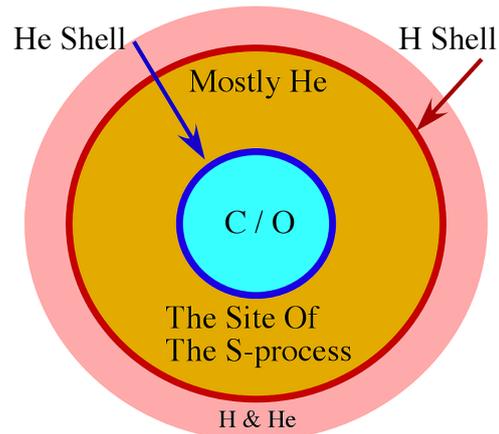


FIGURE 11. The suggested phase in the evolution of a low mass star when the *s*-process takes place.

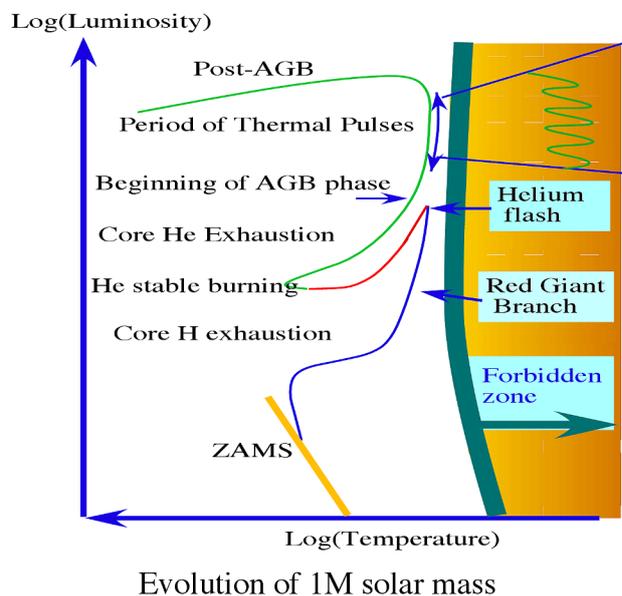


FIGURE 12. The position of the star in the HR diagram during the thermal pulses.

reactions to temperature leads to a steady narrowing of the burning zone. When the shell becomes sufficiently narrow, the negative feedback provided by pressure changes is lost. The volume of a narrow shell is negligible. Consequently its expansion has no effect on the burning, and any small temperature perturbation grows. Burning without effective expansion is unstable. The position of the star in the HR diagram during the phase of thermal pulses is shown in Figs. 12 and 13. This is also the location of the carbon stars, which exhibit unusually high abundances of carbon and *s*-type elements.

An interesting feature is that the two burning shells are never active simultaneously. The oscillation implies that the H-shell and the He-shell provide the luminosity alternatively. Each shell produces a convective zone which developed and decays with the shell’s luminosity. The two convective zones never merge but

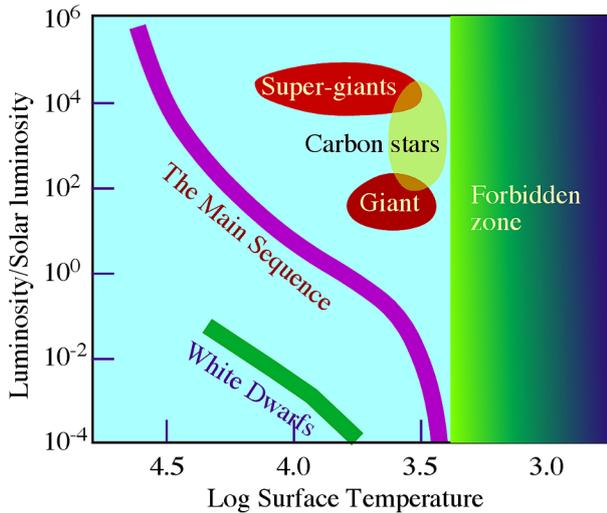


FIGURE 13. The location of the carbon stars in the HR diagram.

do extend, hopefully, over the same region in the star. Thus, the convective zone of the He-shell extends over a limited region well below the H-shell, and produces the HTI elements. After the decay of the He-shell and with it the convective zone and the nuclear reactions, the H-shell becomes unstable and its convective zone expands and possibly reaches the location where the He convective zone left the HTI elements. The H-shell convective zone extends almost to the surface. While the H-convective zone brings fresh hydrogen into the He burning zone, it also removes reaction products and brings them closer to the surface, cf. Fig. 14.

Stars at this phase in their evolution usually have high luminosity and an extensive outer convective zone, and find themselves close to the tip of the Red Giant (cf. Fig. 12).

The problem is that there is conflicting evidence about the process, and the observational results and their interpretations are still not clear.

For example, Charbonnel and do Nascimento found that 96% of evolved stars show a $^{12}\text{C}/^{13}\text{C}$ ratio in disagreement with the standard predictions, and conclude that 96% of low-mass stars do experience an extra-mixing process on the RGB.

Palla et al. [19] examined the planetary nebula NGC 3242, and concluded that the spectrum indicates that the progenitor star did not undergo a phase of deep mixing during the last stages of its evolution, leaving the issue still unsolved.

Pavlenko et al. [20] examined the $^{12}\text{C}/^{13}\text{C}$ ratio in giant stars in globular clusters, and concluded that it suggests complete mixing on the ascent of the red giant branch, in contrast to current models.

Similarly, there are severe numerical difficulties to follow the detailed evolution of the thermal pulses, and we do not know whether what we see in the first two pulses is the same as what happens in the last pulses.

10. SO WHAT HAPPENS?

Have we discovered the B2FH partial mixing idea? The observations and the theory provide conflicting evidence. Different computer codes yield different results, indicating that the fine details are very sensitive to the detailed physics that are assumed. This is both good and bad. Bad because we do not have the answer, and good because it may help investigators to understand the fine physical processes involved. For the moment, we do not know.

11. SOME UNSOLVED PROBLEMS

Probably the greatest unsolved problem is the estimate of the mass loss rate. When no theory is available, we use a dimensionless expression, as follows:

$$\dot{m} = \frac{M}{\tau_{\text{KHR}}} = \frac{M}{\frac{GM^2}{RL}} = \left(\frac{1}{G}\right) \frac{RL}{M} = \eta \frac{R_* L_*}{M_*},$$

where η is a fudge factor. How reliable is the estimate for η ? There is one measurement for Pop II stars. There are half a dozen measurements for Pop I. However the rates appear to be time-dependent, and they vary by a large factor (over 30!)

A short list of unsolved problems: diversity in numerical results, semi-convection, mixing by convection, undershooting and overshooting. Mixing by gravity waves. Rotation and mixing by rotation. The confusion as to what criterion to use, and the extent to which the mixing is partial or complete continues till today (see [5, 8, 14, 16, 18, 23–29]).

Last but not least, how come the universal r process and the s process have practically the same yield? They are produced under completely different conditions.

REFERENCES

- [1] Shaviv, G. *The synthesis of the elements, The astrophysical quest for nucleosynthesis and what it can tell us about the universe*, Springer, Astrophysics and Space Science Library, 387, 2012. This book contains detailed references and a detailed discussion of the s process.
- [2] Burbidge, E.M., Burbidge, G.R., Fowler, W.A. & Hoyle, F., *Rev. Mod. Phys.*, 29, 547, (1957)
- [3] Cameron, A.G.W., *Phys. Rev.*, 93, 932, (1954), *ibid.* *ApJ*, 121, 144, (1955), Cameron, A.G.W., *Bull. Am. Phys. Soc.* II,3, 227, (1958), *Ann. Rev. Nucl. Sci.*, 8, 299, (1958), Chalk River Report CRL-41, 2nd ed., 1958, unpublished
- [4] Cameron, A.G.W., *AJ*, 65, 485, (1960)
- [5] Canuto, V.M., *ApJ*, 534, L1, (2000)
- [6] Charbonnel, C. & do Nascimento, J.D., *A&A*, 336, 915, (1988)
- [7] Fowler, W.A., Burbidge, G.R. & Burbidge, E.M., *ApJS*, 2, 167, (1955). *ApJ*, 122, 271, (1955)
- [8] Gabriel, M., *A&A*, 1, 321, (1969), *Ibid.*, 6, 124, (1970)

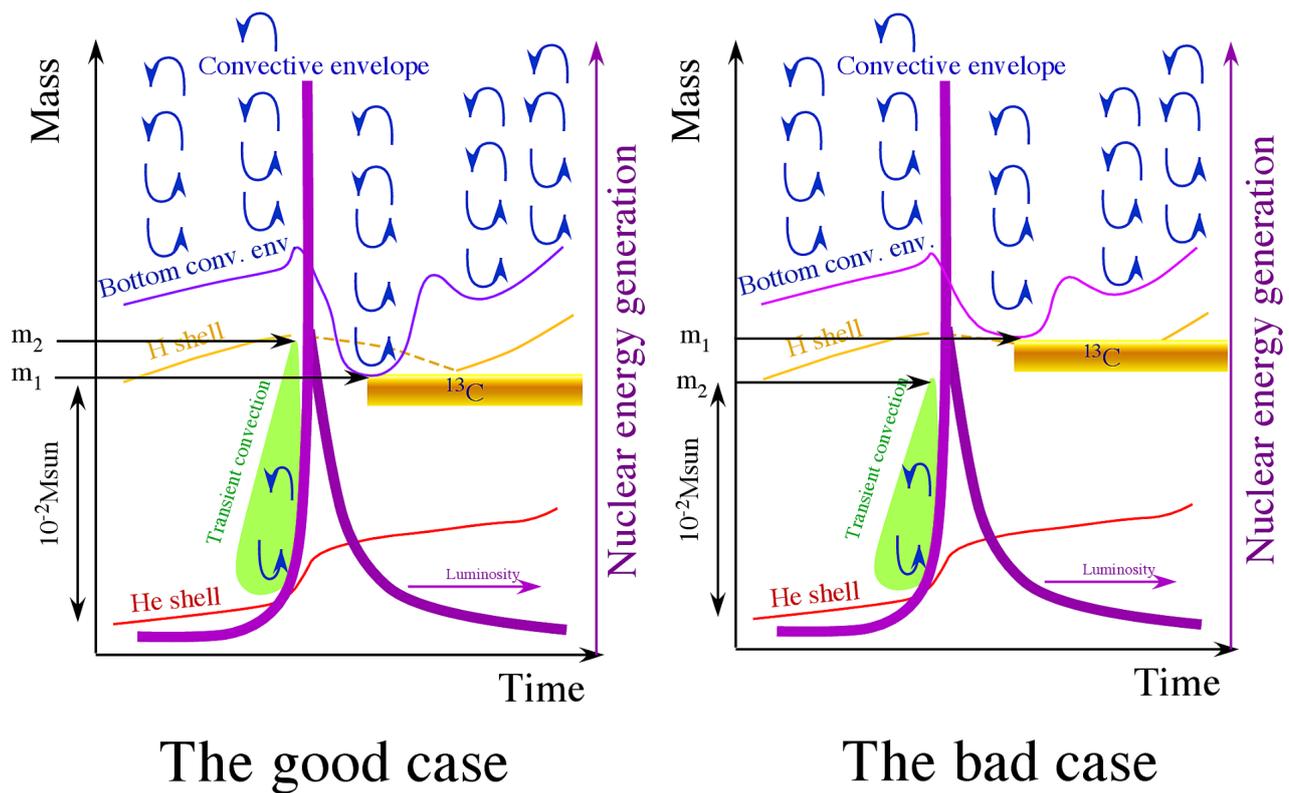


FIGURE 14. The good case in which the convective zones extend over the same region and exchange composition and the bad case where an entropy barrier prevents the two zones from covering the same mass range.

- [9] Grevesse, N. & Anders, E., *Cosmic Abundances of Matter*, Amer. Inst. Phys., ed. Waddington, New York, 1, 1988. Recently, Asplund, M., Grevesse, N., & Sauval, J., in *ASP Conf. Ser. 336, Cosmic Abundances as Records of Stellar Evolution and Nucleosynthesis*, ed. T. G. Barnes, III & F. N. Bash (San Francisco, CA: ASP), 25, (2005) discovered that new models for the solar photosphere yield a total abundance of C, N, O and Ne which is about one-half of the old values.
- [10] Herbig, G.H. & Boyarchuck, A.A., *AJ*, 153, 509, (1974)
- [11] Jaeger, M., and 6 authors, *PRL*, 87, 202501-1, (2001)
- [12] Johnson, E.D., and 17 authors, *PRL*, 97, 192701 (2006)
- [13] Langer, G.E., Kraft, R.P. & Anderson, K.S., *ApJ*, 189, 509, (1974)
- [14] Langer, N., Sugimoto, D., & Fricke, K.J., *A&A*, 126, 207, (1985)
- [15] Kraft, R.P., *S&T*, 48, 18, (1974)
- [16] Kato, *PASJ*, 18, 374, (1966)
- [17] Kipper, T.A. & Kipper, M.A., *Soviet Astron. Lett.*, 3, 220, (1977)
- [18] Merryfield, *ApJ*, 444, 318 (1995)
- [19] Palla, F. et al., *ApJ*, 568, L57, (2002)
- [20] Pavlenko, Y.V., Jones, H.R. & Longmore, A.J. *MNRAS*, 345, 311, (2003)
- [21] Richter, H. , *Sterne*, 72, 73, (1996)
- [22] Richter, G., *AN*, 285, 274, (1960)
- [23] Stothers, R., *MNRAS*, 151, 65, (1970)
- [24] Simpson, E.E., *ApJ*, 165, 295, (1971)
- [25] Stothers, R. & Chin, C.-W., *ApJ*, 198, 407, (1975)
- [26] Sreenivasan, D.J. & Wilson, W.J.F., *Ast. Sp. Sci.*, 53, 193, (1978)
- [27] Stevenson, D.J., *MNRAS*, 187, 129, (1979)
- [28] Spruit, H.C., *A&A*, 253, 131, (1992)
- [29] Shibahashi, H., *Comm. Asteroseismology*, 158, 38th LIAC/HELAS-ESTA/BAG, 2008
- [30] Seeger, P.A., Fowler, W.A. & Clayton D.D., *ApJS*, 11, 121, (1965)
- [31] Suess, H.E., & Urey, H.C., *Rev. Mod. Phys.*, 28, 53, (1956)
- [32] Schönberner, D., In *Hydrogen-deficient Stars*, ASP Conference Series, eds. Werner & Rauch, 391, 139, 2008