EVOLUTION OF CHEMICAL STRUCTURE EXTREME HE-RICH STARS

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1. Introduction

Abundunces of chemical elements observed in various astrophysical objects now are, in general, the result of nucleosynthetic processes occurring in the Universe (primordial and stellar nucleosynthesis). So, the nuclei consisting of integer number of α-particles (^{12}C, ^{16}O, ^{20}N, ...) are the most stable and abundance. Intermediate nuclei (^{14}N, ^{18}F, ...) are not synthesized in the process of helium burning and their abundances do not exceed the value which was at the moment when hydrogen stopped burning.

A theory of element nucleosynthesis, beginning from hydrogen and ending with transuranium nuclei, is studied sufficiently well and only in some details differs from that clear and correct scheme presented by Burbidge et al. (1957). However, along with the examples of exact agreement with the presented scheme of nucleus synthesis, there are some cases which deviate from the scheme of nucleus evolution given in that paper. The observation indicate a few stars with very high helium content and with anomalies in heavy element abundances. As a rule, all of them have low iron abundance, predomination of nitrogen in comparison with carbon and oxigen and great neon fraction (Rolleston, Dufton, Fitzimmons, 1994; Conlon, Dufton, Keenan, 1994; Drilling, Jeffery, Heber, 1998). These and similar anomalies can be produced by mixing of matter between different stellar layers at the stage of layer source (van Winchel, 1997; Marigo, Bressan, Chiosi, 1998).

The most stars where the results of such mixing are observed as chemical anomalies in the athmospheres are the main components of the binary systems (υ Sgr, β Lyr, KS Per...). The characteristics and evolutionary features of these systems are rather close. These systems represent just that rare case of stellar evolution when the star allows the products of nuclear reactions occurred in its internal regions to be studied. Quantitative investigation of processes, which transform the initial chemical composition of the star into the one currently observed, is possible only when the stellar structure and its evolution status are sufficiently known.

The brightness of the stars abovementioned is high enough for photoelectrical and spectroscopical investigations, nevertheless the correctness of determination of their fundamental parameters and evolution status is rather low.

In this paper we analyse their evolutionary status in order to draw some conclusions on internal processes which determine the chemical anomalies presently observed in stars of this type. From our point of view these anomalies are caused by the followings: i) nucleosynthetic processes in the internal layers of the stars; ii) diffuse and convective mixing of matter in the contacting layers; iii) ejection of the surface matter into the interstellar medium. The primary of the system is a helium star which is in the stage of carbon burning in the shell source before neon burst in O-Ne-Mg core. The observed helium stars could be formed in the systems in the process of evolution of their main components after hydrogen burning in the core and after expansion and expulsion of the hydrogen envelope as a result of filling their Roche lobes.

2. Chemical composition of some helium-rich stars

In Table 1 the observed surface abundances of chemical elements of some typical helium-rich stars, their effective temperatures, and surface gravities are presented in comparison with solar ones (Anders, Grevesse,1989; Harris, Lambert, 1984; Harris et al., 1987, 1985, 1988; Leushin, Topilskaya, 1988; Cameron, 1986; Leushin, 2000; Leushin, 2001).

The abundances of elements in these stars are normalized to the unit without allowance for the contribution of elements heavier than ^{20}Ne. In spite of this neglection the main regularities in relative abundances are observed sufficiently clear. First of all this is redistribution for same stars of C, N and O abundances as a result of CNO-cycle processes. Then the characteristic feature of these stars is the increase of the total abundance of the elements of CNO group as compare to the solar one. The exception from the general tendency are some stars, in particular V652 Her and HD 144941, in which the measure abundance of CNO elements is essentially lower than the solar one. β Lyr and υ Sgr are the most bright and well studied among the stars of this group. But since β Lyr is currently at the beginning of the stellar evolution stage studied, the main attention we pay to consideration of the processes mentioned above in υ Sgr.

Table 1: The abundances of light elements in the atmospheres of some helium-rich stars

Star	T_{eff}	lg *g*	H	He	C	N	O	Ne
KS Per	11000	1.1	10^{-4}	0.99	$4\cdot10^{-6}$	0.004	10^{-5}	0.001
β Lyr	12000	2.5	0.16	0.81	0.024	0.001	0.005	-
υ Sgr	13500	1.5	10^{-4}	0.930	0.014	0.023	0.002	0.009
HD 168476	14000	1.5	10^{-4}	0.79	0.032	0.012	0.003	-
LSS 4300	14700	1.4	0.001	0.89	0.01	0.022		-
HD 124448	15750	3.7	10^{-5}	0.85	0.029	0.009	0.004	-
BD+10 2179	16250	3.6	10^{-4}	0.79	0.1	0.009	0.002	-
	16800	2.6	0.001	0.85	0.026	0.001	0.001	-
LSS 3184	23300	3.4	10^{-4}	0.98	0.009	0.002	0.001	-
V652 Her	23500	3.7	0.01	0.98	10^{-4}	0.008	0.001	-
BD-9 4395	22700	2.6	0.001	0.98	0.013	0.001	0.001	-
HD 144541	23200	3.9	0.01	0.98	$5\cdot10^{-5}$	$3\cdot10^{-5}$	10^{-4}	-
Sun	5600	4.3	0.71	0.265	0.004	0.001	0.007	0.002

The stage of fast evolution, in which υ Sgr is at present, is associated with the filling of Roche lobe and small energetic efficiency of nuclear reactions in its interior at considerable luminosity excess. Besides, investigations of chemical composition indicate almost complete loss of hydrogen envelope of the star. Since the hydrogen abundance in the atmosphere of the primary is less than 10^{-4} by mass, then we deal with the remnant in which hydrogen has already burned and the component has passed the stage of purely helium star.

In accordance with the results of numerous calculations (Seidel, 1929; Leushin & Topilskaya, 1987; Dudley & Jeffery, 1990, 1993), the fundamental parameters of the main component of υ Sgr are as follows:

$M = (2.5 \pm 0.4) M_{\odot}$,
$R = (40 \pm 5) R_{\odot}$,
$\lg (L/L_{\odot}) = 4.6 \pm 0.1$,
$Te = (13500 \pm 150)$K,
$\lg g = 1.5 \pm 0.1$.

The structure of helium star with a mass of about $2.5 M_{\odot}$ is very compact. Its radius does not exceed $0.4{-}0.6 R_{\odot}$, its effective temperature should be close to 80 000 K (Paczynski, 1970; 1971). Therefore, the observed values of temperature (10000-13500 K) and radius ($40{-}50 R_{\odot}$) are caused by the envelope. The size of the star is defined by chemical composition and mass of this envelope.

If the hydrogen abundance is considerably less (in case of υ Sgr, $X = 10^{-4}$), then the radius of hydrogen envelope cannot have sizes of $40{-}50 R_{\odot}$ as in υ Sgr. And a thin hydrogen envelope won't give a necessary optical depth for decrease of helium core temperature to the observed value. And therefore, the observed now filling of Roche lobe cannot be caused by the first expansion of the star after hydrogen burning and formation of helium core.

According to Schonberner and Drilling (1983) the currently observed primary of υ Sgr is at the second stage of Roche lobe filling and mass loss (BB case). At the first phase of mass loss the primary has released almost all hydrogen envelope. The remained hydrogen forms a very rarefied envelope of small mass ($M_H/M << 0.1$) over the extended pure helium envelope reaching the sizes of $40{-}50 R_{\odot}$.

The observed characteristics of the primary of υ Sgr impose very strong restrictions on the evolution scenery. In the case of passive role of the secondary, the evolution scenery of the system is defined only by the primary component.

Mass of the secondary is currently $4 M_{\odot}$, that corresponds to a star at the initial main sequence with an effective temperature of $1.5\cdot10^4{-}2\cdot10^4$ K (Chin and Stothers, 1991). In this case luminosity of the secondary in the optical range is about 0.01 of the total luminosity of the system, therefore its spectrum is not observed in the visible range. And in ultraviolet the picture is vice versa. The luminosity of the primary companion in ultraviolet is weakened by strong absorption caused by anomalous chemical composition of its atmosphere. At the same time because of the high effective temperature the secondary contributes strongly to luminosity in this spectrum region.

Since $4 M_{\odot}$ is mass of the component at the present time (this occurred possibly after the first filling of the Roche lobe by the primary and getting of a part of the envelope onto the secondary)

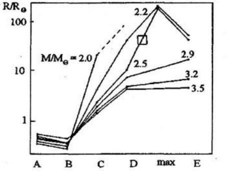

Figure 1: The size of the helium envelope as a function of evolution stage for helium stars of different masses. The letters indicate the evolution stages: A-B – nucleus helium burning in the convective core, B-C – compression of carbon-oxygen core, C-D – carbon burning in the convective core, D-E – neon burning in the core. The square shows the position of the primary component of υ Sgr.

then the initial mass of the secondary could be less than that observed now. All this confirms the above mentioned assumption that evolution of υ Sgr was defined up to now only by the primary component.

Fig. 1 shows helium envelope radius as a function of evolution stage and mass of the star itself (Habets, 1986a,b). According to evolution calculations helium stars with masses less than $2M_\odot$ do not reach the stage of carbon burning in the convective envelope (stage D), their radii decrease at the final stages of evolution as compared to the more massive stars. Helium stars within the mass interval $2.2M_\odot<M<2.9M_\odot$ evolve to the stage of neon burning in the core (stage E). Between the stages D and E, their radii have maximal values ($=250R_\odot$). At further mass increase of helium stars the maximum achieved radius, as well as towards small masses, decreases sharply. Therefore, the observed for υ Sgr radius of the primary ($R=40R_\odot$) imposes restrictions on both component mass ($M=2.5M_\odot$) and its evolution stage (see Fig. 1, position of the primary is shown with the square). Thus, the observed values of mass and radius of the primary of υ Sgr are in good agreement with the theoretically calculated ones for the evolved helium star with the initial mass within $2.0-2.5M_\odot$. Such a helium star could originate in the binary system in the process of evolution of normal component with the initial mass $7\text{-}8M_\odot$ after hydrogen burning in the core, expansion and release of hydrogen envelope as a result of Roche lobe filling. In this case, the mass of the remained helium core will be $2.5M_\odot$. The duration of the process of helium star formation is 40–60 million years (Chin and Stothers, 1991; Maeder and Meynet, 1988; 1989). Further evolution of helium remnant with $2.5M_\odot$ mass is calculated in detail up to the stage of neon burning in O-Ne-Mg core (Habets, 1986a).

From the observed values of luminosity and effective temperature the primary enters the evolutionary track of a helium star with mass $2.5M_\odot$ to the point that corresponds to C-O-Ne core with the layer burning sources of carbon and helium and before the neon flare in the core. The mass of helium shell above the upper zone of nucleus burning is equal approximately to one sollar mass. The living time of the component from the time when it released the hydrogen envelope is about 2.5–2.7 million years, and the duration of the observed phase with the radius that fills the Roche lobe is less than 50000 years. Some other stars presented in Table 1 pass the similar evolution. The differences in chemical contents He-rich stars are connected with distinctions in initial values of dynamic characteristics of binary systems. The dynamic characteristics cause distinctions in evolutionary processes inside a star and result in variations of observable abundances.

Table 2: The contents of light elements in atmosphere of υ Sgr and Sun

Element	On number of atoms $LgN_k/\Sigma N_i$		On weight $lg(\mu_k N_k/\Sigma\mu_i N_i)$	
	υ Sgr	Sun	υ Sgr	Sun
H	-3.40	-0.05	-4.00	-0.15
He	-0.01	-1.00	-0.03	-0.58
C	-2.31	-3.50	-1.85	-2.40
N	-2.15	-4.12	-1.64	-2.95
O	-3.41	-3.28	-2.70	-2.15
Ne	-2.76	-3.90	-2.05	-2.70
Fe	-3.80	-4.50	-2.05	-2.75

Compositions of more abundant elements in the atmosphere of the primary of the system υ Sgr in comparison with the data for the solar atmosphere are listed in Table 2 (Leushin, Topilskaya, 1988).

High abundance of elements of CNO group (0.040 in mass) in comparison with the solar (0.012) and especially high neon abundance (to 0.01) demand extended stages of nucleus burning at least up to neon synthesis.

Moreover, if the initial chemical composition, suffered evolutionary nucleus changes, was similar to the solar one then the observed excess of the total abundance of CNO-elements demands corresponding nucleus processes. And if carbon increase as a factor of 3.5, as compared to that in the Sun, can be explained by conversion of ^{4}He into ^{12}C, then nitrogen increase as a factor of 20 is a more complicated problem, since nitrogen is synthezed at hydrogen burning in CNO cycle only from carbon and at rather high temperatures from oxigen also. During this cycle carbon converts into nitrogen, but the total abundance of CNO elements does not change transforming into equilibrium quantity at which relation of nitrogen and carbon is $^{14}N/^{12}C = 10^2-10^3$. Thus, nitrogen abundance can not be higher than the total abundance of C, N and O. The following stages of nucleus evolution (up to iron formation) change abundances of He, C, O, Ne and so on, while nitrogen abundance remains practically unchanged.

The two above mentioned peculiarities in abundances of light elements in the atmosphere of the primary of υ Sgr do not agree with theoretical calculations of stellar evolution. The modern evolution theories state that rather intensive mixing of zones of various nucleus burning and those free from burning do not exist. According to the theoretical calculations the products of nucleus burning remain in those layers where the reactions of this type occurred, and the element in the star are located in layers (Masevich, Tutukov, 1988; de Jager, 1984; Haiashi et al., 1962). Therefore, if we observe in the primary the shell consisting of helium, that is formed from hydrogen in CNO cycle reactions, then there must not be higher neon abundance than in the initial matter. As a rule, chemical composition of the initial matter for the stars, being formed, is solar in which neon abundance is equal to 0.002, and the total abundance of CNO elements is 0.012. At the same time for υ Sgr these values are essentially higher.

We could understand a great carbon overabundance in υ Sgr, if we observe a layer in which helium burning process had begun converting helium into carbon in triple a-process. However, here, as it was mentioned above, along with the carbon overabundance we observe essentially higher nitrogen and neon abundances. And what is more the total value of C, N, O and Ne abundances is essentially higher than the initial one. The data on C, N, O and Ne elements are obtained with a good accuracy and need careful considerations.

We may suppose that the matter observed in the υ Sgr and other stars atmospheres was originated due to at least two nucleus burning sources. If in the period of the first expansion of the component, helium core compression and helium flare the core is convective, and at the same time at the boundary of the core hydrogen is burning in the envelope, then there occurs exchange (mixing) of matter between zones of helium and hydrogen burning. In this case in the region of hydrogen burning additional synthesis of nitrogen is possible from carbon thrown there from the zone of helium burning. This process is simultaneous and increased carbon and nitrogen abundances sharply accelerate hydrogen burning with all circumstances that follows after this.

If at the moment of this exchange there occur expansion and release of the outer layers (that are not in reactions) either on the component or out of the system, then we can observe just that part of the star where hydrogen burning in CNO cycle takes place, and in the region with carbon overabundance. The fact, that oxygen abundances in the Sun and υ Sgr are similar and neon abundance is sharply increased, imposes restrictions on mixing rate and on temperature of helium burning in the core.

3. Nucleus reactions of CNO cycle and triple α-process

Below we consider possible theoretical scheme of formation of the observed chemical composition of the helium-reach stars. Main attention at calculations is paid to CNO cycle in the zone of hydrogen burning. The zone of helium burning is interesting in our case only from the view point of chemical composition of the matter which is diffused from this zone. The triple α-process is the main nucleus reaction here. Generation of nuclei that follow after carbon is taken into consideration only for oxygen ^{16}O and ^{20}Ne, since the formation rate of other nuclei (^{24}Mg, ^{28}Si and etc.) are negligibly small.

The theory of CNO cycle, beginning from Bethe (1939) is described in detail many times. The total scheme of nucleus reactions of hydrogen burning in high temperature reactions represents some connected circles: CN, NO, OF, FNe... with formation of α-particles from protons in each of them. For our calculations we used all the reactions of the first two circles. The third circle of CNO cycle

$$^{16}O \to {}^{17}F \to {}^{17}O \to {}^{18}F \to {}^{18}O \to {}^{15}N \to {}^{16}O$$

is not closed here, since the reaction in the second channel at interaction of ^{17}O with proton

$$^{17}O + {}^{1}H < \begin{matrix} ^{14}N + {}^{4}He \\ ^{18}F + \gamma, \end{matrix}$$

which gives ^{18}F and leads to formation of this circle, has a very low rate. And slow reactions in the third circle cause small corrections of the results of the first two circles. The same can be said according to all following circles.

Except hydrogen reactions we included into calculations helium reactions, that is, triple α-process and neutron formation reactions from the nuclei of ^{13}C. Thus, for calculations of chemical evolution we use the following set of reactions. Reactions of CNO cycle:

$$\begin{array}{ll} ^{12}C + {}^{1}H \to {}^{13}N + \gamma & \\ \quad ^{13}N \to {}^{13}C + \beta^{+} + \nu & \\ ^{13}C + {}^{1}H \to {}^{14}N + \gamma & \text{CN cycle} \\ ^{14}N + {}^{1}H \to {}^{15}O + \gamma & \\ \quad ^{15}O \to {}^{15}N + \beta^{+} + \nu & \\ ^{15}N + {}^{1}H \to {}^{12}C + {}^{4}He & \\ ^{15}N + {}^{1}H \to {}^{16}O + \gamma & \text{NO cycle} \\ ^{16}O + {}^{1}H \to {}^{17}F + \gamma & \\ \quad ^{17}F \to {}^{17}O + \beta^{+} + \nu & \\ ^{17}O + {}^{1}H \to {}^{14}N + {}^{4}He & \text{OF cycle.} \end{array}$$

Reactions of helium burning:

$$\begin{array}{l} ^{4}He + {}^{4}He + {}^{4}He \to {}^{12}C + \gamma \\ \quad ^{12}C + {}^{4}He \to {}^{16}O + \gamma \\ \quad ^{13}C + {}^{4}He \to {}^{16}O + n \\ \quad ^{16}O + {}^{4}He \to {}^{20}Ne + \gamma \end{array}$$

The fact that all these reactions proceed both forward and backward is taken into consideration.

The rates of the given reactions are taken from data by Leng (1978), Fowler, Cauglan, Zimmerman (1975) and NACRE – http://pntpm.ulb.ac.be/nacre.htm (Angulo et al., 1999). The character of cross sections of the calculated nucleus reactions and the physical conditions in the system investigated indicate that the process of hydrogen burning, continuing for rather a long time, takes place at equilibrium values of concentrations ^{12}C, ^{13}C, ^{14}N and ^{15}N, which grows very slowly due to burning of ^{16}O (three last reactions of CNO cycle, which we took into considerations). The nuclei of ^{14}N formed from oxygen transform simultaneously into equilibrium concentrations of the above mentioned four isotopes. Such character of hydrogen burning process allows us to use equilibrium conditions for calculations at different stages.

For each moment of time the quantity of ^{14}N originated from ^{16}O is calculated. Then, the equilibrium ratios of isotopes of the CN cycle are recounted taking into account this change. Just the same procedure (analogous set of equations) was used for calculations of equilibrium relations of isotopes in two circles of CNO cycle (CN and NO). In this case we obtain additionaly equilibrium concentrations ^{16}O, ^{17}O and ^{17}F. Equilibrium in this circle is reached during the time comparable with the time of hydrogen burning and therefore this procedure can be used only for control of calculations.

The evolution of mass nucleus concentrations are determined by the following equations:
$dX(i)/dt = A_i(\pm\Sigma\langle bj\rangle X(j)/A_j \pm \Sigma\langle b.j.k\rangle X(j)/A_jX(k)/A_k$,
where $X(i)$ is the mass concentration of the i-th element, A_i is the atomic weight of the corresponding nucleus. The first sum in the right part is taken from all j for one-particle nucleus reactions, the second - from j and k for two-particle reactions.

The final value of mass concentration of each element at the time moment $T-X_T(i)$, in accordance with the above mentioned, is defined by numerical integration in time ($X_0(i)$ – the initial value of concentration).

We carried out a number of calculations of chemical composition changes caused by CNO cycle. An interval of the used temperatures is (15–50) 10^6K, an interval of densities 5–100 g/cm^3. The initial chemical composition is close to the solar one; $X(H)=0.7$, $X(C)=0.005$, $X(N)=0.001$, $X(O)=0.009$. Some results of these calculations are given in Tables 2 and 3. Thus the time of hydrogen burning (decrease of its abundance to 0.02 in mass) under stationary conditions (constant temperature, density and absence of mixing) is from $1.5 \cdot 10^3$ years (for $T=50 \cdot 10^6$ K and $\rho=100$ g/cm^3) to 10^{13} years (for $T=15 \cdot 10^6$ K and $\rho=5$ g/cm^3). Almost all the time the burning proceeds at equilibrium in the CN cycle, which is attained for a much shorter time (0.15 years in the first case and $2.7 \cdot 10^8$ years in the second).

Table 2: The time (in sec) of entering to the equilibrium hydrogen burning in CN cycle

ρ, g/cm^3	T_9, K				
	0.015	0.020	0.030	0.040	0.050
5	$8 \cdot 10^{15}$	$5 \cdot 10^{13}$	10^{11}	$2 \cdot 10^8$	10^8
10	$4 \cdot 10^{15}$	$3 \cdot 10^{13}$	$5 \cdot 10^{10}$	$6 \cdot 10^7$	$5 \cdot 10^7$
20	$2 \cdot 10^{15}$	$1.5 \cdot 10^{13}$	$3 \cdot 10^{10}$	$4 \cdot 10^7$	$2 \cdot 10^7$
25	$1.5 \cdot 10^{15}$	10^{13}	$1.5 \cdot 10^{10}$	$3 \cdot 10^8$	$1.8 \cdot 10^7$
50	$9 \cdot 10^{14}$	$6 \cdot 10^{12}$	10^{10}	$2 \cdot 10^8$	10^7
100	$4 \cdot 10^{14}$	$4 \cdot 10^{12}$	$6 \cdot 10^9$	10^8	$5 \cdot 10^6$

Table 3: The time (in sec) of hydrogen burning in CN cycle up to $X(H)=2 \cdot 10^{-2}$

ρ, g/cm^3	T_9, K				
	0.015	0.020	0.030	0.040	0.050
5	$3 \cdot 10^{20}$	$6 \cdot 10^{17}$	10^{15}	10^{13}	$5 \cdot 10^{11}$
10	10^{20}	$3.5 \cdot 10^{17}$	$4 \cdot 10^{14}$	$6 \cdot 10^{12}$	$2.5 \cdot 10^{11}$
20	$5 \cdot 10^{19}$	$1.5 \cdot 10^{17}$	$2 \cdot 10^{14}$	$2 \cdot 10^{12}$	10^{11}
25	$3 \cdot 10^{19}$	10^{17}	$1.5 \cdot 10^{14}$	$1.8 \cdot 10^{12}$	$9 \cdot 10^{10}$
50	$1.5 \cdot 10^{19}$	$6 \cdot 10^{16}$	10^{14}	10^{12}	$7 \cdot 10^{10}$
100	10^{19}	$3 \cdot 10^{16}$	$3.5 \cdot 10^{13}$	$4 \cdot 10^{11}$	$4.5 \cdot 10^{10}$

In the process of hydrogen burning the abundances of the main isotopes change by two steps.

At the first stage all carbon is converted to nitrogen, at the second stage, covering all the period of hydrogen burning, oxygen is gradually transformed to nitrogen and to equilibrium concentrations of ^{12}C, ^{13}C, ^{14}N and ^{15}N. The character of these changes is presented in Table 4 and Fig. **2**.

4. The internal structure of the stars during the mixing stage

The data from Tables 2-4 show that some variants of calculations can not be realized by the present moment in our Universe, since the time of these processes exceeds the age of the Universe. At the same time under certain physical conditions, which exist, in particular, in the star under study, for all the stages of the CNO cycle to be realized short time intervals are required that can well fall in time within the corresponding stages of evolution of the star.

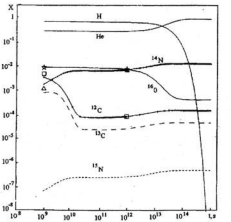

Figure 2: Dynamics of nucleosynthesis in the star at $T=3 \cdot 10^6$ K, $\rho=25$ g/cm^3 and initial chemical composition: $X(H)=0.7$, $X(CNO)=0.015$ before termination of hydrogen burning. The signs show the initial and equilibrium values of ^{12}C, ^{14}N, ^{16}O abundances.

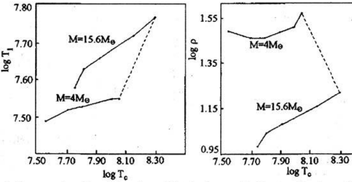

Figure 3: Temperature T_1 and density ρ of the hydrogen shell source for stars of different masses as a function of temperature T_c at the centre (from calculations of Haiashi et al., 1962).

Table 4: Mass abundance of different isotopes after hydrogen burning in the layer above the helium core

T_9, K	ρ, g/cm^3	t, s	H	He	^{12}C	^{13}C	^{14}N	^{15}N	^{16}O	^{17}O
0.015	5.0	.1E+22	.53E-08	.98E+00	.39E-04	.12E-04	.10E-01	.53E-06	.18E-02	.23E-02
	20.0	.1E+21	.49E-03	.98E+00	.40E-04	.12E-04	.10E-01	.53E-06	.18E-02	.24E-02
	100.0	.1E+20	.22E-01	.96E+00	.39E-04	.12E-04	.10E-01	.53E-06	.19E-02	.24E-02
0.020	5.0	.5E+19	.16E-11	.98E+00	.83E-04	.26E-04	.13E-01	.60E-06	.12E-02	.50E-04
	20.0	.5E+18	.17E-04	.98E+00	.84E-04	.26E-04	.13E-01	.60E-06	.12E-02	.51E-04
	100.0	.1E+18	.17E-04	.98E+00	.84E-04	.26E-04	.13E-01	.60E-06	.12E-02	.51E-04
0.030	5.0	.1E+16	.48E-02	.98E+00	.17E-03	.52E-04	.13E-01	.55E-06	.47E-03	15E-06
	20.0	.1E+16	.11E-08	.98E+00	.16E-03	.52E-04	.13E-01	.55E-06	.46E-03	.15E-06
	100.0	.2E+15	.11E-08	.98E+00	.16E-03	.52E-04	.13E-01	.55E-06	.46E-03	.15E-06
0.040	5.0	.5E+14	.87E-08	.98E+00	.25E-03	.78E-04	.13E-01	.49E-06	.27E-03	.42E-07
	20.0	.2E+13	.40E-01	.94E+00	.25E-03	.79E-04	.14E-01	.49E-06	.28E-03	.43E-07
	100.0	.1E+13	.49E-03	.98E+00	.25E-03	.79E-04	.14E-01	.49E-06	.27E-03	.43E-07

The stars presented in Table 1 may be conditionally divided into three groups with general evolution scenarios: the first group – υ Sgr and LSS 4300 in which overabundance of N and general increase of elements of CNO group are observed. They formed their chemical abundances before the stars lost its hydrogen envelope in the period of evolution when the layer hydrogen burning above the helium core was in progress. At the same time helium burning took place in the core, which began shortly after the onset of the core compression. During the compression time, according to theoretical calculations of evolution, the temperature at the centre rises from a few tens million degrees to hundreds million degrees, the central density being increased by more than 3 orders (see, for instance, Maeder and Meynet, 1988; Chin and Stothers, 1991). At the same time, physical characteristics in the region of shell, source of hydrogen burning at the boundary of helium core change much less.

Fig. 3 shows the relationship between temperature and density of the layer source and temperature at the centre, which grows as a result of compression (Haiashi et al., 1962). As it is seen from these data the temperature varies here by a factor of 1.1-1.5, while the density changes even less. Helium flash at the centre (and hence termination of the core compression, which caused the temperature and density to increase) for stars of different masses occurs with the parameters shown by the dashed lines in Fig. 3.

Thus for a star of $7M_\odot$ the parameters of the layer source must be close to the following: $T=40$–10^6 K and $\rho=20$ g/cm^3. Since the temperature and density inside the helium core decrease rather slowly and at the boundary the decrease rate of these quantities rises sharply, then the de pth of the layer source is very small and its mass is 10^{-4}–$10^{-6}M_\odot$.

According to our assumptions, it is this layer that entraps matter enriched in carbon from the helium burning zone. On the one hand, this carbon, when transforming to nitrogen, changes the abundance of the CNO group elements, and on the other hand, accelerates transformation of hydrogen to helium, increasing thus energy release in the layer. This additional energy release can stimulate instability of the inner parts of the star, mixing and thermal pulsations (Marigo et al., 1998). The dependence of the chemical composition of the core region upon the time (derived for T=180 · 10⁶K and ρ=3.15 · 10³ g/cm³) is shown in Fig. 4. From this region additional carbon is supplied to the layer source of hydrogen burning amount.

The whole period of formation of the observed chemical composition by the mechanism considered here takes, depending on the adopted physical conditions (first of all on the values of mixing parameters), from 5 to 10 million years (47–57 million years of evolution from the initial main sequence) (Maeder, Meynet, 1988; 1989; Chin and Stothers, 1991). The temperature at the centre changes in this period from $100 \cdot 10^6$ to $200 \cdot 10^6$ K, the central density $\rho_c=2.7 \cdot 10^3-7.0 \cdot 10^3$ g/cm³. The decrease in temperature and density within the helium core is smooth and slow enough and can be described by a polytrope, but at the boundary the temperature and density undergo an abrupt change. The temperature at the boundary of the hydrogen layer source drops from a few tens million to a few hundreds thousand degrees, the density decreases from hundreds to tens of g/cm³.

The carbon-oxygen-neon core at the final stage of helium burning has a mass of $1-1.3M_\odot$; this core is surrounded by a helium shell of $1-1.2M_\odot$, at the upper boundary of which nuclear hydrogen burning in the layer takes place. The mass of this layer is $10^{-4}-10^{-6}M_\odot$. Thus a star with a mass of $7M_\odot$ has a very complex He-C-O-Ne core of a total mass of $2.1-2.6M_\odot$ surrounded by a hydrogen envelope of $4.9-4.4M_\odot$. The observed component of υ Sgr is exactly this core, that remained after loss of the whole hydrogen envelope. Apparently, evolution run of LSS 4300 is the same that we propose for υ Sgr. The initial stage of identical process is, apparently, observed in β Lyr, which has not lost yet its hydrogen envelope.

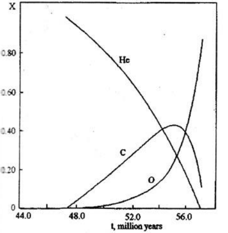

Figure 4: Variation of chemical composition of the core region of the star with the temperature $2 \cdot 10^8$ K and log g=3.5 when carbon is synthesized from helium.

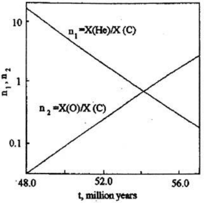

Figure 5: He/C and O/C ratios as a function of time for the core region of a star of $7M_\odot$.

The helium star with a mass of $2.5M_\odot$ evolves very fast, expanding the envelope (now helium) up to 40–50 solar radii, i.e. it is transformed to the observed component off υ Sgr. The chemical composition of the observed atmosphere of the primary is formed precisely in the considered period in down the hydrogen envelope, in the layer of hydrogen burning above the He-C-O-Ne core. And if at this moment there exists faint mixing between the helium burning and hydrogen burning zones, then we can get a chemical composition with the above described peculiarities.

The physical structure of the considered stars in the stage of formation of the observed chemical composition was responsible for the no-uniform distribution of elements along the star radius. The varying abundances of the He, C, and O nuclei in the helium core are shown in Fig. 4 for $T=1.8 \cdot 10^8$ K and lg ρ=3.5. At these temperature, and density values helium burns in the core of a star with $M=7M_\odot$. The ratios between mass concentrations X(He)/X(C) and X(O)/X(C) for such a core, depending on time, are presented in Fig. 5. The nitrogen abundance in the core is constant and is within – $X_0(N)+X_0(C)=X(N)=X_0(N)+X_0(C)+X_0(O)$ depending on the amount of oxygen converted to nitrogen in hydrogen burning in the CNO cycle. The zero indicates the initial values of concentrations of the corresponding elements. The chemical composition of the helium envelope is defined by the conditions in the CNO cycle and the results of calculation for the corresponding parameters.

Initial abundances of elements in the zone of shell hydrogen burning depend on the time of the CNO cycle action up to the moment of mixing with the matter from the core and on the initial conditions. Thus for the modeling of the chemical composition that is produced in the zone of the shell source of hydrogen with the presence of mixing, it is necessary to allow for the content of three zones mentioned. The initial chemical composition of the mixture in the zone of hydrogen burning is calculated proceeding from the following assumptions.

a) Matter in the zones of hydrogen and helium burning can be taken in any stage of transformation, i.e. hydrogen abundance can be varied from the initial (X=0.7) to the final (X=0); the same refers to helium (from Y=0.285 to Y=0).

b) The ratio between the isotopes of C and N in the zone of hydrogen burning is taken equilibrium. The oxygen abundance is defined by the amount of burned hydrogen.

c) The chemical composition of matter from the helium burning zone is determined by the parameters: $n_1 = X(^4\mathrm{He})/X(^{12}\mathrm{C})$ and $n_2 = X(^{16}\mathrm{O})/X(^{12}\mathrm{C})$. The nitrogen abundance here is fixed and is equal to «equilibrium» for the CNO cycle in the zone of hydrogen burning.

d) The portion of matter brought to the zone of hydrogen burning (M_2) is determined by the parameter $n_3 = M_2/M_1$ where M_1 is the mass of matter in the hydrogen burning zone.

e) The portion of matter dredged up from the helium burning zone (M_o) that is mixed with matter of the helium shell, is determined by the parameter $n_o = M_o/M_2$.

Then the initial chemical composition in the hydrogen burning zone is produced in two stages in the following manner:

i) Mixing of matter of the core and helium shell.

ii) Diffusion of matter with the formed composition to the hydrogen burning zone. The composition of the helium shell is determined by the parameters:

CNO – total initial mass concentration of the CNO group elements,

$X_o(\mathrm{O})$ – amount of oxygen unburned in the CNO cycle which is determined by appropriate calculations.

Then the mass concentrations in the shell will be the following:

$X(\mathrm{He})_{\mathrm{env}} = 1 - \mathrm{CNO}$,
$X(\mathrm{C})_{\mathrm{env}} = 0$,
$X(\mathrm{N})_{\mathrm{env}} = \mathrm{CNO} - X_o(\mathrm{O})$,
$X(\mathrm{O})_{\mathrm{env}} = X_o(\mathrm{O})$.

The mass concentrations at the centre of the star:

$X(\mathrm{He})_{\mathrm{nuc}} + X(\mathrm{C})_{\mathrm{nuc}} + X(\mathrm{N})_{\mathrm{nuc}} + X(\mathrm{O})_{\mathrm{nuc}} = 1$,
$X(\mathrm{He})_{\mathrm{nuc}} = n_1 X(\mathrm{C})_{\mathrm{nuc}}$,
$X(\mathrm{C})_{\mathrm{nuc}} = (1 - X(\mathrm{N})_{\mathrm{nuc}})/(n_1 + n_2 + 1)$,
$X(\mathrm{N})_{\mathrm{nuc}} = \mathrm{CNO} - X_o(\mathrm{O})$,
$X(\mathrm{O})_{\mathrm{nuc}} = n_2 X(\mathrm{C})_{\mathrm{nuc}}$.

After mixing in the helium shell the chemical composition will be:

$X(\mathrm{He})_{\mathrm{env}} = (1 - \mathrm{CNO} + n_o X(\mathrm{He})_{\mathrm{nuc}})/(1 + n_o)$,
$X(\mathrm{C})_{\mathrm{env}} = n_o X(\mathrm{C})_{\mathrm{nuc}}/(n_o + 1)$,
$X(\mathrm{N})_{\mathrm{env}} = \mathrm{CNO} - X_o(\mathrm{O})$,
$X(\mathrm{O})_{\mathrm{env}} = (X_o(\mathrm{O}) + n_o X(\mathrm{O})_{\mathrm{nuc}})/(1 - n_o)$.

In the core and in the shell it is sufficient to take into account only the main isotopes – ^{4}He, ^{12}C, ^{14}N and ^{16}O. Matter with the obtained composition is dredged up from the shell to the hydrogen burning zone in different stages, then is mixed and transformed in the nuclear reactions. The final composition in the hydrogen burning zone is calculated for all isotopes taking into account the relation:

$X(^1\mathrm{H}) + X(^4\mathrm{He}) + X(^{12}\mathrm{C}) + X(^{13}\mathrm{C}) + X(^{14}\mathrm{N}) + X(^{15}\mathrm{N}) + X(^{16}\mathrm{O}) + X(^{17}\mathrm{O}) = 1$.

The corresponding concentrations are:

$X(^1\mathrm{H}) = X(^1\mathrm{H})/(1 + n_3)$,
$X(^4\mathrm{He})_{\mathrm{layer}} = (X(^4\mathrm{He}) + n_3 X(^4\mathrm{He})_{\mathrm{env}})/(l + n_3)$,
$X(^{12}\mathrm{C})_{\mathrm{layer}} = (X(^{12}\mathrm{C}) + n_3 X(^{12}\mathrm{C})_{\mathrm{env}})/(l + n_3)$,
$X(^{13}\mathrm{C})_{\mathrm{layer}} = X(^{13}\mathrm{C})/(1 + n_3)$,
$X(^{14}\mathrm{N})_{\mathrm{layer}} = (X(^{14}\mathrm{N}) + n_3 X(^{14}\mathrm{N})_{\mathrm{env}})/(l + n_3)$,
$X(^{15}\mathrm{N})_{\mathrm{layer}} = X(^{15}\mathrm{N})/(l + n_3)$,
$X(^{16}\mathrm{O})_{\mathrm{layer}} = (X(^{16}\mathrm{O}) + n_3 X(^{16}\mathrm{O})_{\mathrm{env}})/(l + n_3)$,
$X(^{17}\mathrm{O})_{\mathrm{layer}} = (X(^{17}\mathrm{O})/(1 + n_3)$.

Thus changing the input parameters n_o, n_1, n_3 and $X_o(\mathrm{O})$, one may change the rate and degree of mixing in different stages of helium burning in the core and hydrogen burning in the shell.

5. Structure extreme He-rich Stars and Conclusions

Using the above described model of chemical composition change in different stellar zones, we can simulate the process of formation of the observed abundances of light elements in the atmospheres of the considered stars. Varying the model parameters, we can obtain the agreement with the results of observations of elements in different helium-rich stars. The procedure described was used in details in calculations for obtaining agreement with the chemical composition of the most unique star υ Sgr. For this purpose we made a series of calculations of nucleosynthesis with different parameters of mixing. Since there can be numerous variants of such calculations, we restricted their number, proceeding from the most likely assumptions.

The carbon-oxygen core with a mass of $1.3M_\odot$ is surrounded by a helium envelope with a mass of $1.2M_\odot$. At the bottom of this envelope helium is burning, while at the upper boundary (in the layer with a mass of 10^{-4}–$10^{-6}M_\odot$) hydrogen burning occurs. Above is the hydrogen envelope with a mass $4.5M_\odot$.

Since the mass of the helium envelope is sufficiently large, and the mixing between the core and this shell must not be very intensive for the inhomogenety in the core and the star as a whole to be preserved, we have considered the variants when

Table 5: Concentration of elements in different zones of the star with varied parameters of mixing

Model			Mass concentration of elements								
			X_0			X			X_e		
n_1	n_0	n_4	C	N	O	C	N	O	C	N	O
1	0.2	0.5	0.068	0.015	0.028	0	0.056	0.007	0.021	0.043	0.017
2	0.2	0.07	0.050	0.015	0.010	0	0.045	0.002	0.004	0.043	0.00
2	0.25	0.25	0.060	0.015	0.013	0	0.050	0.003	0.012	0.043	0.005
2	0.026	0.33	0.062	0.015	0.013	0	0.052	0.004	0.015	0.043	0.006
2	0.27	0.4	0.065	0.015	0.014	0.001	0.054	0.004	0.018	0.043	0.007
2	0.3	0.5	0.07	0.015	0.015	0.001	0.057	0.004	0.023	0.043	0.007

a mass of 0.05–0.5 of the helium envelope mass is dredged up to the helium shell. At the same time, since the mass of the hydrogen burning shell is small, then the ratio between the shell mass and the mass dredged up was supposed to be equal to unity. Besides, we varied the chemical composition of matter transferred from the helium burning zone (n_1=X(He)/X(C) and n_2=X(O)/X(C)). The value of n_1 varied from 10 to 0.5. A certain stellar evolution stage (at the stage of shell helium burning) and a definite value of n_2 correspond for each selected value of n_1, that proceeds from the relation between n_1 and n_2 and the time shown in Fig. 6. These relations have been obtained from the calculation results of helium burning in the reactions

^{4}He(2α, γ)^{12}C and ^{12}C(α, γ)^{16}O

at a temperature $T=1.8 \cdot 10^8$ and $r=3.15 \cdot 10^3$ (the temperature and density correspond to a star with a mass of $M=7M_\odot$ in the period of helium burning). We may be found many variants for which the total number of the CNO elements or the nitrogen abundance will coincide with those observed in υ Sgr, none of the variants with the equilibrium distribution of N and C (X(N)/X(C)=5.5) alone can give the carbon - nitrogen ratio (X(N)/X(C)=0.043/0.012=3.3) observed in υ Sgr. Thus to explain the observed chemical composition, we make another assumption that the reaction products of the shell hydrogen source after hydrogen completely burned out continued mixing with matter of the helium envelope enriched in carbon.

Table 5 shows the distributions of C, N and O in stars close in mass to those observed in υ Sgr, which can be obtained as a result of varying mixing parameters.

As it was mentioned above, n_1 in Table 5 characterizes the composition of matter dredged up from the shell helium source to the helium envelope and therefore the evolutionary stage. The amount of this matter is characterized by the value of n_0. The mass ratio of the corresponding element in the helium envelope after mixing is denoted by parameter X_0, while for the shell hydrogen source after mixing and hydrogen burning by X. At last, X_e is the mass ratio of the element after the final mixing of hydrogen burning products in the layer with matter from the helium envelope.

The parameter n_4 denotes the mass proportion, mixed into matter of the layer hydrogen source after the termination of hydrogen burning.

A comparison of the C, N and O abundances observed in the atmosphere of υ Sgr

(X(C)=0.012, X(N)=0.043, X(O)=0.008)

with the data from Table 5 shows that within the accuracy the observed values are in good agreement with the theoretical, the fit being the best when

X_e(C)=0.012, X_e(N)=0.043, X_e(O)=0.005,

here n_1=2, n_0=0.25 and n_4=0.25.

Besides, for n_1=2, n_0=0.26 and n_4=0.33 the corresponding calculated abundances are

X_e(C)=0.015, X(N)=0.043, X_e(O)=0.006,

which is also close enough to the observed values.

Thus it can be stated that the observed abundances of the C, N and O elements in the atmosphere of υ Sgr were generated about five million years ago in a star that had not lost its thick hydrogen envelope. This moment came approximately after $52 \cdot 10^6$ years of evolution of the star with the initial mass $7M_\odot$ from the main sequence. By that time the amount of helium in the shell helium source was still twice that of synthesized carbon (n_1=2). About a quarter of the core mass (n_0=0.25–0.26) containing He, C and O (X(He)/X(C)=2, X(O)/X(C)=0.21) was mixed with the helium envelope and the mixture, having been dredged up to the shell hydrogen source, was momentarily (for about 10000 years) converted to helium and nitrogen. Then the products of nuclear hydrogen burning were mixed with matter of helium envelope again after hydrogen had been depleted. The amount of mass dredged up from the helium envelope was 0.25–0.3 of the hydrogen shell source mass. Just at this moment hydrogen envelope release completed and chemical composition of the star became such as we observe now.

The problem neon also is solved within the framework of the offered model. Neon is one of most abundant (after helium and nitrogen) elements in the atmosphere υ Sgr. Neon is formed as a result of reactions helium with carbon and oxygen

^{12}C (α,γ) ^{16}O (α,γ) ^{20}Ne

in a core of a star, and then arise from the mixing in those layers of a star, which are now observed in result of losses of an envelope. In this case we should assume, what in a core of υ Sgr during helium burning in three α-process the carbon promptly turned to oxygen, and last in neon. The formation of neon in a nuclear chain with nitrogen is simultaneously possible

$$^{14}N\ (\alpha,\gamma)\ ^{18}F\ (\beta^{+},\nu)\ ^{18}O\ (\alpha,\gamma)\ ^{22}Ne.$$

Taking into account, that in υ Sgr the large contents of nitrogen, we should assume, that the generation neon goes simultaneously with generation of nitrogen. The mixing between hydrogen-burning and helium-burning zones results in that generated in a helium-burning zone the carbon having got in shell a source burning of hydrogen will be transformed to nitrogen. Substance enriched by nitrogen in turn getting in a helium-burning zones increases quantity neon, which then is again arise the top layers. Thus, the simultaneous enrichment and nitrogen and neon is created.

Such situation is possible in another He-rich stars. The change of parameters of mixing at different stages of evolution can result in various features of observable abundances.

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