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Evolution of chemical composition of the main component in the binary system υ Sagittarius

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Abstract. A model is proposed of evolution of the interior composition of the peculiar binary system, which explains the observed anomalous chemical composition of the main component atmosphere ($X(\mathrm{H}) = 10^{-4}; X(\mathrm{He}) = 0.844; X(\mathrm{C}) = 0.013; X(\mathrm{N}) = 0.042$). It is supposed that 5 million years ago the primary was in the stage of hydrogen burning in the shell over the helium core, where the helium–carbon reactions took place. Due to convective mixing, the synthesized carbon diffused into the hydrogen–burning zone. There carbon was converted into nitrogen in the CN–cycle reactions that caused an anomalously high nitrogen abundance. The throw–off of the outer layers of the star that occurred later disclosed the layer mentioned, which is presently the atmosphere of the main component with the observed chemical anomalies. The abundances of all elements calculated in the frames of this model are consistent with the observational data. The quantitative restrictions on temperature and density in the corresponding layers and values of mixing parameters have been obtained. Agreement with observations is shown to be the best provided that the mass of matter penetrating into the helium layer from the zone of helium–carbon reactions is ~ 25 % of the helium–carbon core mass. At the same time the ratio of mass concentrations He/C in this matter must be equal to 2, while the portion of mass diffusing into the layer of hydrogen burning may be varied between 1/3–1/4 of the layer mass.

Key words: stars: binary system — evolution: individual (υ Sgr) — chemical composition

1. Introduction

The ratio of light element abundances which is observed in the majority of normal stars, in the Sun, in meteoritic matter and in the whole solar system, disregarding hydrogen and helium, which dominate in the Universe from the time of the Big Bang nucleosynthesis, reflects events occurring in the equilibrium nuclear process. As a result of this process, the nuclei consisting of α–particles – ^{12}C, ^{16}O, ^{20}Ne, etc. become the most overabundant. Just the same occurs in the course of nuclear processes beginning with helium burning which produce ^{12}C, ^{16}O and others. Intermediate nuclei (^{14}N, ^{18}F), however, are not synthesized in the process of helium burning and their abundance do not exceed that at the moment of hydrogen burning termination.

The total abundance of heavy elements prior to helium burning cannot significantly differ from their primeval abundance either. Therefore, if in a star, whose atmosphere is nearly all-helium, a comparatively large number of heavier elements is observed too, while the mass of nitrogen is about 4 per cent (that is more than the total abundance of heavy elements in the most metal-rich stars), such a composition of stellar material is then difficult to explain within the standard evolution theory.

A theory of nucleosynthesis, beginning with hydrogen and ending with transuranium nuclei, has been developed in sufficient details and only partially differs from the clear and correct scheme presented by Burbidge et al. (1957). However, along with the examples of exact consistency with the presented scheme of nucleosynthesis, there are some cases which deviate from the scheme of nuclear evolution given in that paper. This is just the case with υ Sgr.

υ Sgr is a unique system and represents just the rare case of stellar evolution when the star allows the products of nuclear reactions that occurred in its interior regions to be studied. In this sence υ Sgr resembles another unique system, β Lyr, however, in the first case we deal with the system evolved much further. Quantitative investigation of processes, which transformed the initial chemical composition of the star into the composition currently observed, is possible only provided that the knowledge of the stellar structure is reliable enough.

The brightness of υ Sgr ($m = 4.26 - 4.41$) is high enough for photoelectric and spectroscopic investigations, nevertheless there has been no unambiguous opinion even on its fundamental parameters up to now, and hence determinations of its evolutionary status are contradictory. We attempt here to coordinate all the parameters in order to obtain consistent principal parameters and determine evolutionary status of υ Sgr.

In the previous papers (Leushin, Topilskaya, 1985; 1987; 1988a,b), where υ Sgr system was analysed from the spectrograms obtained with the Main Stellar Spectrograph of the 6 m telescope, we presented the values of effective temperatures, acceleration of the surface gravity and chemical composition of the atmosphere. Here we use these data together with the available data on mass and radius of the components for determination of the evolutionary status of υ Sgr.

From our point of view the system is being observed in the period when it has entered a very short evolution stage about $\sim$ 50000 years long. The primary of the system is a helium star which is in the stage of carbon burning in the shell source before the neon burst in the O–Ne–Mg core. The observed helium star could be formed in the system in the process of evolution of the normal component after hydrogen burnt out in the core and after the expansion and expulsion of the hydrogen envelope as a result of filling its Roche lobe.

2. Mass and radius of the υ Sgr primary

The most important point in analysing the history of the observed chemical composition of the υ Sgr atmosphere is to define its main characteristics. The brightness and uniqueness of this system attracts attention of many researchers, that is why it has been given a detailed sdudy. There are estimates of practically all characteristics. However, the obtained results differ greatly and do not agree with each other.

Table 1 lists the data on υ Sgr, available in literature. The large spread of the values of the parameters is explained by both the complexity of analysis of this system and measurement errors. The mass function value

$$f(M) = M_2^3/(M_1 + M_2)^2 \cdot \sin^3 i$$

is between 1.5–2.0. It is difficult to say which of these values is true. However, analysing the bulk of data, we may assume that $f(M) = 1.6 \pm 0.1$ is the most reliable. The boundary values of the mass function allow us to estimate the limits in which the masses of the υ Sgr components lie.

For the largest value of $f(M)$ at $\sin i \approx 1$ and different values of $q = M_1/M_2$ the masses of the components are

$$f(M) = 2.0; q = 0.3; M_1 = 1.1M_\odot \text{ and } M_2 = 3.4M_\odot,$$

$$q = 1.0; M_1 = 16M_\odot \text{ and } M_2 = 16M_\odot.$$

Though these values are presented in Table 1, the mass of 16 solar masses is hardly true for helium star, and themass of 1 solar mass for the primary is not in good agreement with the other parameters of the system.

Dudley and Jeffery (1990) have obtained the mass ratio q from the examination of the orbits of the primary and secondary, the measurements for the latter being done in the ultraviolet spectrum region. In other spectral regions the secondary is not visible. The obtained value is close to the mean from the first two and is equal to $q = 0.63$. The mass values at such q are

$$f(M) = 2.0; q = 0.63; M_1 = 3.3M_\odot, M_2 = 5.1M_\odot.$$

The mass function value used in the present paper, $f(M) = 1.5$, is close to the most probable and gives more real mass values for the components:

$$f(M) = 1.5; q = 0.63; M_1 = 2.5M_\odot, M_2 = 4.0M_\odot.$$

Thus, the mass value of the primary of υ Sgr obtained from measurements of its orbit is most likely between $2.5 - 3.4M_\odot$.

The next fundamental parameters of the components are the radii of each of the stars (R). Table 2 presents the radius values for the primary from the values of T_e and $\lg(L/L_\odot)$ given in Table 1.

$$(\lg(R/R_\odot) = 0.5 \cdot \lg(L/L_\odot) + 2 \cdot \lg T_e + 7.52).$$

An independent radius value can be obtained from the gravity acceleration determined spectroscopically (Leushin, Topilskaya, 1985) and the mass value, which was estimated above

$$\lg R = 0.5 \cdot (\lg g_\odot + \lg M - \lg g) = 2.2 + 0.5 \cdot (\lg M - \lg g).$$

The effective temperature ($T_e = 13500$ K) and gravity ($\lg g = 1.5$) values, determined from the analysis of the continuous and line spectra (Leushin, Topilskaya, 1985; 1987), give slightly different radius values: $R = 40R_\odot$ (from T_e) and $R = 50\,R_\odot$ (from $\lg g$). However, it is necessary to take into account that $\lg g$=1.5 is the effective acceleration of gravity (g_e) in the atmosphere of the star, which is always less than the dynamical determined by the mass and radius of the star. Therefore, if we take into consideration that

$$g = G \cdot M/R = g_e + dg,$$

where dg may reach 0.1–0.5 (Merezhin, 1986), then from $\lg g$ we obtain the same radius value as from T_e. Thus, from the above mentioned it may be deemed that the fundamental parameters of the primary of υ Sgr must be as follows:

Table 1: *Parameters of υ Sgr*

$f(M)$	q	$M_1/M_\odot$	$M_2/M_\odot$	$R_1/R_\odot$	$R_2/R_\odot$	sin$i$	$a \cdot \sin i/R_\odot$	T_e	lg$L$	lg g	Ref.
1.6											Wilson, 1914
1.7							135				Seydel, 1929
2.0	1.5	15	10	50		1	150			2.2	Hack et al.,1962
								13000			Lee,Nariai, 1967
							130				Nariai, 1967
									4.7		Davignan et al., 1979
	0.5	4.8	6.9			0.73	130			1.8	Hack et al.,1980
	1.3	13	10	140	180	0.96	154	13000		1.3	Hellings et al., 1981
	0.3	1	3	50		1	90	10000		1.0	Schonberner, Drilling, 1983
	0.3	1	3	29.7				10500	4.0		Rao, Venugopal, 1985
	0.33	1	3						4.3		Parthasarathy et al., 1986
								13500		1.5	Leushin,Topilskaya, 1987
			11								Morrison, 1988
1.5	0.63	2.5	4.0	60		1	210		4.6	1.3	Dudley, Jeffery, 1990
								11800			Dudley, Jeffery, 1993

Table 2: *The radius value of the primary ($R/R_\odot$)*

	T_e				lg g		
lg $L/L_\odot$	13500	13000	10000	M	1.3	1.5	1.7
4.67	39	42	71	2.5 59	47	37	
4.01	18	20	32	2.9	63	50	40
				3.3	68	54	43

$M = (2.9 \pm 0.4)M_\odot$,
$R = (40 \pm 5)R_\odot$,
$\lg(L/L_\odot) = 4.6 \pm 0.1$,
$T_e = (13500 \pm 150)K$,
$\lg g = 1.5 \pm 0.1$.

3. Evolutionary status of υ Sgr

The stage of fast evolution in which υ Sgr is at present is associated with the filling of the Roche lobe and the small energetic efficiency of nuclear reactions in its interior with considerable luminosity excess. Besides, investigations of chemical composition indicate almost complete loss of the 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 a remnant in which hydrogen has already burned and the component has passed the stage of a purely helium star.

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

Fig. 1 shows the relationship of the envelope size above the helium zone with the mass $2.5M_\odot$ upon the hydrogen abundance and mass of the envelope itself. This relationship is obtained from the data calculated by Snezhko (1969). This shows that even with a high hydrogen abundance ($X = 0.5 - 0.8$) and a relatively large mass (0.1–0.15 of the star mass) its size above the helium star cannot exceed $10R_\odot$. If the hydrogen abundance is considerably lower (in the case of υ Sgr, $X = 10^{-4}$), then the radius of the hydrogen envelope cannot have sizes of $40 - 50R_\odot$ as in υ Sgr. The thin hydrogen envelope will not give a necessary optical depth to reduce the temperature of the helium

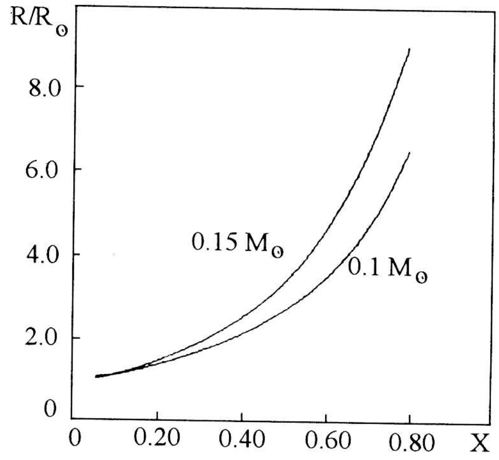

Figure 1: *The relationship of the envelope size ($R/R_\odot$) over the helium zone and the concentration of hydrogen X(H) and envelope mass M.*

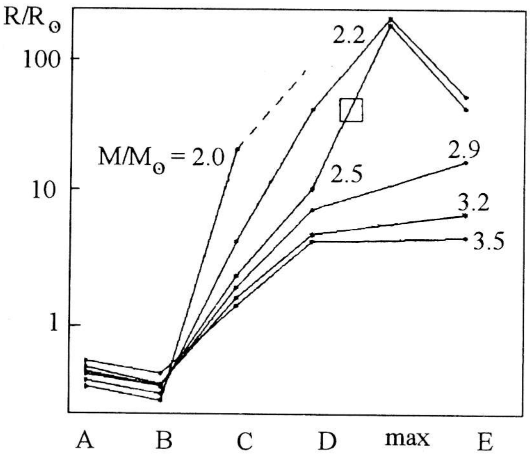

Figure 2: *The size of the helium envelope as a function of evolution stage for helium stars of different masses. The letters indicate the evolution stages: A–B — nucleus helium burning in the convective core, B–C — compression of carbon–oxygen core, C–D — carbon burning in the convective core, D–E — neon burning in the core. The square shows the position of the primary component.*

core to the observed value. Therefore, the observed now filling of the Roche lobe cannot be caused by the first expansion of the star after hydrogen burning and formation of the helium core.

According to Schonberner and Drilling (1983) the currently observed primary of υ Sgr is in the second stage of the Roche lobe filling and mass loss (BB case). At the first phase of mass loss the primary has lost almost all hydrogen envelope. The rest hydrogen forms a very rarefied envelope of small mass ($M_r/M << 0.1$) above the expanding pure helium envelope that has reached a size of $40 - 50R_\odot$.

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

The mass of the secondary is currently about $4M_\odot$, which corresponds to a star on the initial main sequence with an effective temperature of 15000–20000 K (Chin and Stothers, 1991). In this case the luminosity of the secondary in the optical range is about 0.01 of the total luminosity of the system, that is why its spectrum is not observed in the visible range. And in the ultraviolet the reverse takes place. The luminosity of the primary in the ultraviolet is weakened by strong absorption caused by the anomalous chemical composition of its atmosphere. At the same time, because of the high effective temperature, the secondary contributes essentially to the luminosity in this spectrum region. These circumstances allow us to obtain a radial velocity curve (Dudley and Jefferi, 1990) and a sufficiently reliable value of $q = M_1/M_2$ from the ultraviolet observations. The mass estimate of the secondary, $4M_\odot$, which is consistent with the observations, makes it possible to estimate the time after which this component begins to influence essentially the evolution run of the system. This time is equal to the evolution time of the component on the main sequence (200–300 million years). Since $4M_\odot$ is the mass of the component at the present time (possibly it became such after the first filling of the Roche lobe by the primary and dredge–up of part of its envelope onto the secondary), then the initial mass of the secondary could be smaller than the mass observed now. All this confirms the above stated assumption that evolution of υ Sgr has been defined up to now only by the development of the primary component.

Fig. 2 shows the 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 smaller than $2M_\odot$ do not reach the stage of carbon burning in the convective envelope (stage D), their radii decrease sharply in the final stages of evolution as compared to more massive stars. Helium stars within the mass interval $2.2M_\odot < M < 2.9M_\odot$ evolve as far as the stage of neon burning in the core (stage E). Between the stages D and E their radii have maximum values ($\approx 250R_\odot$). With further mass increase of helium stars the maximum achievable radius, as well as towards smaller masses, decreases sharply. Therefore, the observed radius of the primary ($R = 40R_\odot$) sets

Table 3: *Abundances of light elements in the atmospheres of the Sun and υ Sgr*

Element	υ Sgr	Sun
H	10^{-4}	0.710
He	0.844	0.265
C	0.013	0.004
N	0.042	0.001
O	0.007	0.007
Ne	0.089	0.008

a limit on both the component mass ($M = 2.5M_\odot$) and its evolution stage (see Fig. 2, the position of the primary is shown by the square).

Thus the observed values of mass and radius of the primary of υ Sgr are in excellent agreement with the theoretical for an evolved helium star with an initial mass between $2.0 - 2.5M_\odot$. Such a helium star could originate in the system in the process of evolution of the normal component with an initial mass of $7M_\odot$ after the core hydrogen burning, expansion and dredge–up of hydrogen envelope as a result of the Roche lobe filling. In this case, the mass of the remaining helium core will be $2.5M_\odot$. The time of helium star formation is 40–60 million years (Chin and Stothers, 1991; Maeder and Meynet, 1988; 1989). Further evolution of the helium remnant of $2.5M_\odot$ is calculated in detail up to the stage of neon burning in the O–Ne–Mg core (Habets, 1986a).

From the observed values of luminosity and effective temperature the primary evolve to the evolutionary track of the helium star with the mass $2.5\mathrm{M}_\odot$ to the point that corresponds to the C–O–Ne core with the shell carbon and helium burning sources before the neon flash in the core. The mass of the helium shell above the upper zone of nuclear burning is equal approximately to one solar mass. The life time of the component from the time when it lost its 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.

4. Chemical composition of the main component of υ Sgr

Contents of the most abundant elements in the atmosphere of the primary of the system in comparison with the data for the solar atmosphere (Leushin, Topilskaya, 1988a) are listed in Table 3.

The enhanced abundance of the CNO-group elements (0.062 in mass) in comparison with the solar (0.012) and the especially high neon abundance (to 0.090) demand advanced stages of nuclear burning at least until neon synthesis.

Moreover, if the initial chemical composition that suffered evolutionary nuclear changes was similar to solar, then the observed excess of the total number of CNO elements demands appropriate nuclear processes. And if the carbon enhancement by a factor of 3, as compared with solar, can be explained by conversion of ^{4}He to ^{12}C, then the nitrogen increase by a factor of 40 is a more complicated problem, since nitrogen is synthesized at hydrogen burning in the CNO cycle only from carbon and at sufficiently high temperatures from oxigen too. During this cycle carbon converts into nitrogen, but the total number of CNO elements does not change, transforming into equilibrium state in which the nitrogen–carbon ratio is $^{14}\mathrm{N}/^{12}\mathrm{C} = 10^2 - 10^3$. Thus the nitrogen abundance can not be higher than the sum of initial abundances of C, N and O. The next stages of nuclear evolution (until iron formation) change abundances of He, C, O, Ne, while the 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 there is no intensive mixing between the zones of different core burning and those free from burning. According to the theoretical calculations the products of nuclear burning remain in those layers where the reactions of this type occurred, and the elements 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 transformed from hydrogen in the CNO–cycle reactions, then there must not be higher neon abundance than in the initial matter. As a rule, the chemical composition of the initial matter for stars being formed is solar, in which the neon abundance is equal to 0.008, while the total abundance of CNO elements is 0.012. At the same time for υ Sgr these values are essentially higher. The last situation could be understood if for the CNO group of υ Sgr large carbon excess was observed, then we would deal with the layer where the helium burning process that transforms helium to carbon in the triple α–process started. 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, and O abundances is essentially higher than the initial aone. The neon overabundance may be supposed to be erroneous, since its content has been determined from very weak lines in the visible spectrum region (Leushin, Topilskaya, 1988a). So we exclude neon problem from consideration. The data on C, N and O elements are obtained with a good accuracy and need further studying.

It may be assumed that matter observed in the υ Sgr atmosphere originated due to operation of at least two nuclear burning sources. If in the period of the first expansion of the component, helium core compression and helium flash the core is convective, and at the same time at the boundary of the core hydrogen is burning in the envelope, then exchange (mixing) of matter between the zones of helium and hydrogen burning may occur. In this case in the region of hydrogen burning additional synthesis of nitrogen is possible from carbon brought there from the zone of helium burning. This process is momentary and the enhanced carbon and nitrogen abundances sharply accelerate hydrogen burning with all ensuing consequences.

If at the moment of this exchange expansion and dredge–up of the outer layers (that are not involved in the reactions) either to the component or out of the system occur, then we will observe precisely the part of the star where hydrogen burning in the CNO cycle took place, in the region with carbon overabundance. The fact that the oxygen abundance in the υ Sgr is practically the same as in the Sun, while the neon abundance is sharply increased, imposes restrictions on the mixing rate and on the temperature of the core helium burning.

Below we try to consider quantitatively possible mechanisms of nucleosynthesis which caused the observed chemical composition of υ Sgr.

5. Nuclear reactions of the CNO cycle and the triple α–process

We consider one of the pure theoretical possibilities of formation of the observed chemical composition of the υ Sgr primary. Main attention in the calculations is paid to the CNO cycle operation in the zone of hydrogen burning. The zone of helium burning is interesting to us only from the view point of chemical composition of matter which is diffused from this zone. We think that the triple α–process is the main nuclear reaction here. Generation of nuclei that follow carbon is taken into consideration only for oxygen ^{16}O, since the formation rate of the other nuclei (^{20}Ne,^{24}Mg and etc.) is negligibly low. The very high neon abundance in the atmosphere of υ Sgr found by Leushin and Topilskaya (1988a), though it is not considered here, may point to the fact that this simplification is probably not correct and needs a closer scrutiny. However, here we restrict ourselves only to this notice, since, as it was mentioned above, there can be serious errors in the estimate of neon abundance (this problem needs additional investigations).

The theory of the CNO cycle, beginning from Bethe (1939) is described in detail in many textbooks and scientific papers, nevertheless here we consider the CNO cycle in order to explain some methodical matters used in calculations. The total scheme of nuclear reactions of hydrogen burning in high temperature reactions represents some chains: 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 chains. The third ring of the CNO cycle

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

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

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

which gives ^{18}F and leads to formation of this chain, has a very low rate. Slow reactions in the third chain cause small corrections of the results of the first two chains. The same refers to all the next chains.

Besides the reactions with hydrogen the reactions with helium were included in the program of calculations, namely, the triple α–process and the reactions of formation of neutrons from the ^{13}C nuclei. Thus for the calculation of chemical composition evolution we use the following set of reactions.
CNO-cycle reactions:

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

Reactions of helium burning:

$$\begin{array}{ccccccccc}
^{4}\mathrm{He} & + & ^{4}\mathrm{He} & + & ^{4}\mathrm{He} & \rightarrow & ^{12}\mathrm{C} & + & \gamma \\
 & & ^{12}\mathrm{C} & + & ^{4}\mathrm{He} & \rightarrow & ^{16}\mathrm{O} & + & \gamma \\
 & & ^{13}\mathrm{C} & + & ^{4}\mathrm{He} & \rightarrow & ^{16}\mathrm{O} & + & n
\end{array}$$

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

6. Cross–sections of nuclear reactions

The rates of the given reactions $< bij >$ according to Leng (1978) are given below; i and j are mass numbers of the initial and the final nucleus, T_9 – the temperature in units of 10^9 K, ρ – the matter density in g/cm^3. Under physical conditions considered in this paper the greater part of the reactions takes place only in the first chain of the cycle. The reaction rates are known here with a good accuracy and the calculated equilibrium ratios of isotopes are confirmed by numerous observations.

CNO cycle:

$$
\begin{aligned}
<b1213>/\rho = {} & 2.043 \cdot 10^7/T_9^{2/3} \cdot exp(-13.69/T_9^{1/3} \\
& -(T_9/1.5)^2) \cdot (1 + 0.0304 T_9^{1/3} + \\
& +1.19 T_9^{2/3} + 0.254 T_9 + \\
& +2.06 T_9^{4/3} + 1.12 T_9^{5/3}) + \\
& +1.081 \cdot 10^6/T_9^{3/2} \cdot exp(-4.925/T_9) + \\
& +2.153 \cdot 10^5/T_9^{3/2} \cdot exp(-18.179/T_9),
\end{aligned}
$$

$$
\begin{aligned}
<b1314>/\rho = {} & 8.006 \cdot 10^7/T_9^{2/3} \cdot exp(-13.717/T_9^{1/3} \\
& -(T_9/2)^2) \cdot (1 + 0.0304 T_9^{1/3} + \\
& +0.958 T_9^{2/3} + 0.204 T_9 + \\
& +1.39 T_9^{4/3} + 0.753 T_9^{5/3}) + \\
& +1.352 \cdot 10^6/T_9^{3/2} \cdot exp(-5.978/T_9) + \\
& +2.661 \cdot 10^5/T_9^{3/2} \cdot exp(-11.987/T_9) + \\
& +2.262 \cdot 10^6/T_9^{3/2} \cdot exp(-13.463/T_9),
\end{aligned}
$$

$$
\begin{aligned}
<b1415>/\rho = {} & 5.08 \cdot 10^7/T_9^{2/3} \cdot exp(-15.228/T_9^{1/3} \\
& -(T_9/3.09)^2) \cdot (1 + 0.0274 T_9^{1/3} - \\
& -0.778 T_9^{2/3} - 0.149 T_9 + \\
& +0.261 T_9^{4/3} + 0.127 T_9^{5/3}) + \\
& +2.282 \cdot 10^3/T_9^{3/2} \cdot exp(-3.011/T_9) + \\
& +1.65 \cdot 10^5/T_9^{3/2} \cdot exp(-12.007/T_9),
\end{aligned}
$$

$$
\begin{aligned}
<b1516>/\rho = {} & 9.78 \cdot 10^8/T_9^{2/3} \cdot exp(-15.251/T_9^{1/3} \\
& -(T_9/0.45)^2) \cdot (1 + 0.0273 T_9^{1/3} + \\
& +0.219 T_9^{2/3} + 0.042 T_9 + \\
& +6.83 T_9^{4/3} + 3.32 T_9^{5/3}) + \\
& +1.11 \cdot 10^4/T_9^{3/2} \cdot exp(-3.388/T_9) + \\
& +1.49 \cdot 10^4/T_9^{3/2} \cdot exp(-4.665/T_9) + \\
& +3.8 \cdot 10^6/T_9^{3/2} \cdot exp(-11.048/T_9),
\end{aligned}
$$

$$
\begin{aligned}
<b1512>/\rho = {} & 8.157 \cdot 10^{11}/T_9^{2/3} \cdot exp(-15.251/T_9^{1/3} \\
& -(T_9/0.522)^2) \cdot (1 + 0.0273 T_9^{1/3} + \\
& +6.74 T_9^{2/3} + 1.29 T_9) + \\
& +1.29 \cdot 10^8/T_9^{3/2} \cdot exp(-3.676/T_9) + \\
& +3.144 \cdot 10^8/T_9^{3/2} \cdot exp(-7.974/T_9).
\end{aligned}
$$

The equilibrium state in the second chain of the cycle, if at all, is attained only at the very end of hydrogen burning. The reaction $^{15}N(p,\gamma)^{16}O$, which results in ^{16}O formation, proceeds slowly, and since the abundance of ^{16}O is much higher than that of ^{15}N, then after practically momentary establishing equilibrium in the CN cycle (the first chain of the triple CNO cycle) conversion of ^{16}O to ^{14}N takes place, which enhances the abundance of elements in the first chain and establishes equilibrium in the second chain of the cycle.

Besides, because of the poor assurance in the values of the cross–sections of the reactions

$$^{16}O(p,\gamma)^{17}F(e^+,\nu)^{17}O \text{ and } ^{17}O(p,\alpha)^{14}N$$

the calculations may be performed with different approximations of the values < b1617 > and < b1714 >, some of which do not bring about equilibrium in the ON chain at all. Under certain physical conditions equilibrium is not reached because the process of hydrogen burning is completed well before oxygen and other nuclei are at equilibrium. Nevertheless, this chain of the CNO cycle is important since it changes the abundance of ^{14}N (and all isotopes of the first chain) and hence accelerates the process of hydrogen burning.

We present four sets of formulae for Solpiter cross–sections of these reactions. The first two (Leng, 1978) differ only by coefficients (1,2). The same refers to formula (3) given by Fowler et al. (1975). In the last formula (4), an expression given by Reeves (1970) for < b1617 > takes into account electronic screening (term with $\rho^{0.5}$), while the formula for < b1714 > is derived from the data of Brown (1962) who calculated the cross–section of the reaction $^{17}O(p,\alpha)^{14}N$ allowing for interference of resonance levels of the nucleus ^{17}O. We present Brown's data as a fifth–degree polynomial of temperature.

1. Leng (1978):

$$
\begin{aligned}
<b1617>/\rho = {} & 9.54 \cdot 10^7/T_9^{2/3} \cdot exp(-16.692/T_9^{1/3}) \cdot \\
& \cdot (1 + 0.00843 \cdot T_9^{1/3}), \\
<b1714>/\rho = {} & 1.53 \cdot 10^7/T_9^{2/3} \cdot exp(-16.712/T_9^{1/3} - \\
& -(T_9/0.565)^2) \cdot (1 + 0.025 \cdot T_9^{1/3} + \\
& +5.39 \cdot T_9^{2/3} + 0.94 \cdot T_9 + 13.5 \cdot T_9^{4/3} + \\
& 5.98 \cdot T_9^{5/3}) + 2.92 \cdot 10^6 T_9 \cdot exp(-4.247/T_9).
\end{aligned}
$$

2. Leng (1978):

$$
\begin{aligned}
<b1617>/\rho = {} & 3.556 \cdot 10^5/T_9^{0.81} \cdot exp(-16.692/T_9^{1/3}) \cdot \\
& \cdot (1 + 0.00843 T_9^{1/3}), \\
<b1714>/\rho = {} & 1.53 \cdot 10^7/T_9^{2/3}(1 + 19.986 T_9)^{0.8333} \cdot \\
& \cdot exp(-16.712/T_9^{1/3} - (T_9/0.565)^2) \cdot \\
& \cdot (1 + 0.025 \cdot T_9^{1/3} + 5.39 \cdot T_9^{2/3} + \\
& +0.94 \cdot T_9 + 13.5 \cdot T_9^{4/3} + 5.98 \cdot T_9^{5/3}) + \\
& +2.92 \cdot 10^6 T_9 \cdot exp(-4.247/T_9).
\end{aligned}
$$

3.Fowler et al. (1975):

$$
\begin{aligned}
<b1617>/\rho = {} & 1.64 \cdot 10^8/T_9^{2/3} \cdot exp(-16.696/T_9^{1/3}) \cdot \\
& \cdot (1 + 0.025 \cdot T_9^{1/3} - 1.31 \cdot T_9 2/3 -
\end{aligned}
$$

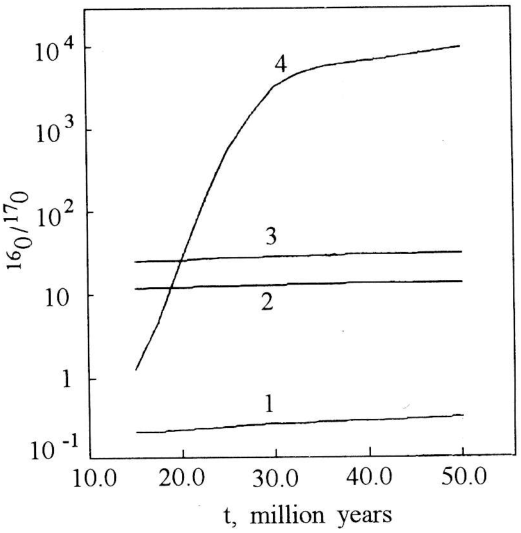

Figure 3: *Equilibrium of* $^{16}O/^{17}O$ *ratio as a function of temperature, calculated for different cross–sections. 1, 2 – Leng (1987), 3 – Fowler et al. (1975), 4 – Reeves (1970) and Brown (1962).*

$$-0.229 \cdot T_9 + 0.673 \cdot T_9^{4/3} + 0.299 \cdot T_9^{5/3}),$$
$$< b1714 > /\rho = 1.91 \cdot 10^9 / T_9^{2/3} \cdot exp(-16.712/T_9^{1/3}).$$

4. Reeves (1970):

$$< b1617 > /\rho = 1.7 \cdot 10^8 / T_9^{2/3} \cdot exp(-16.696/T_9^{1/3}) \cdot (1 + 0.025 \cdot T_9^{1/3} - 1.27 \cdot T_9^{2/3} - 0.222 \cdot T_9) \cdot (1 + 0.633 \cdot 10^{-4} / T_9^{3/2} \cdot \rho^{0.5}).$$

Brown (1962):

$$< b1714 > /\rho = exp(2.303(-19.8922 - 1881.31 \cdot T_9 + 221406 \cdot T_9^2 - 8226460 \cdot T_9^3 + 1.33585 \cdot 10^8 \cdot T_9^4 - 8.09148 \cdot 10^8 \cdot T_9^5)).$$

Table 4 gives the cross–section values for different temperatures.

Fig. 3 is a plot of equilibrium ratios $^{16}O/^{17}O$ calculated for the corresponding cross–sections vrs temperature.

Observations of abundances of different oxygen isotopes (Table 5) show that there are no objects in which the $^{16}O/^{17}O$ ratio would be smaller than a few hundred, and this means that concentrations of ^{16}O and ^{17}O (during CNO cycle) are defined by reactions with cross–sections corresponding to curve 4 in Fig. 3, i.e. by the formulae given by Reeves (1970) and Brown (1962).

The cross–sections of backward reactions of the CNO cycle, according to the data of Leng (1978) are

$$< b1312 > = 0.8841 \cdot 10^{10} T_9^{3/2} \cdot exp(-22.554/T_9) \cdot < b1213 >,$$
$$< b1413 > = 1.1900 \cdot 10^{10} T_9^{3/2} \cdot exp(-87.625/T_9) \cdot < b1314 >,$$
$$< b1514 > = 2.6690 \cdot 10^{10} T_9^{3/2} \cdot exp(-84.692/T_9) \cdot < b1415 >,$$
$$< b1215 > = 0.706 \cdot exp(-57.631/T_9) \cdot < b1512 >,$$
$$< b1615 > = 3.6240 \cdot 10^{10} T_9^{3/2} \cdot exp(-140.741/T_9) \cdot < b1516 >,$$
$$< b1716 > = 0.3034 \cdot 10^{10} T_9^{3/2} \cdot exp(-6.97/T_9) \cdot < b1617 >,$$
$$< b1417 > = 0.6757(\cdot xp(-13.845/T_9) \cdot < b1714 >.$$

Since the life time of nuclei subject to β-radioactivity is very short ($^{13}N - 870\,s$, $^{15}O - 178\,s$ and $^{17}F - 95\,s$) the reactions of β–decay may be assumed to proceed momentarily and the corresponding nuclei are transformed immediately to decay products, therefore the reactions of β–decay were not taken into account in the calculations.

The cross–sections of helium burning reactions according to Leng (1978) are

$$< b0412 > = 9.36 \cdot 10^{-10} (\rho \cdot X(He))^2 / T_9^3 \cdot exp(-4.411/T_9) + 1.66 \cdot 10^{-8} \cdot (\rho \cdot X(He))^2 / T_9^3 \cdot exp(-27.443/T_9),$$
$$< b1216 > /\rho = 0.903 \cdot 10^8 / T_9^2 \cdot exp(-32.12/T_9^{1/3} - (T_9/5.863)^2) \cdot (1 + 0.621 T_9^{2/3})^2 / (1 + 0.047/T_9^{2/3})^2 + 2.74 \cdot 10^7 / T_9^{2/3} \cdot exp(-32.12/T_9^{1/3}) + 1.25 \cdot 10^3 / T_9^{3/2} \cdot exp(-27.499/T_9) + 1.43 \cdot 10^{-2} T_9^5 \cdot exp(-15.541/T_9),$$
$$< b1316 > /\rho = 6.769 \cdot 10^{15} / T_9^{2/3} \cdot exp(-32.329/T_9^{1/3} - (T_9/1.284)^2) \cdot (1 + 0.0129 T_9^{1/3}) + 3.82 \cdot 10^5 / T_9^{3/2} \cdot exp(-9.373/T_9) + 1.41 \cdot 10^6 / T_9^{3/2} \cdot exp(-11.873/T_9) + 2.00 \cdot 10^9 / T_9^{3/2} \cdot exp(-20.409/T_9) + 2.92 \cdot 10^9 / T_9^{3/2} \cdot exp(-29.283/T_9).$$

Allowance for backward reactions of helium burning was made with the cross–sections

$$< b1204 > = 2.003 \cdot 10^{20} T_9^{3/2} \cdot exp(-84.424/T_9) \cdot < b0412 > /\rho^2,$$
$$< b1612 > = 5.133 \cdot 10^{10} \cdot exp(-83.110/T_9) \cdot < b1216 >,$$
$$< b1613 > = 5.792 \cdot exp(-25.707/T_9) \cdot < b1316 >.$$

7. Equilibrium processes in the CNO cycle

The character of cross–sections of the calculated nuclear reactions and the physical conditions in the sys-

Table 4: *Cross–section values of the reactions* $^{16}\mathrm{O}(\mathrm{p},\gamma)^{17}\mathrm{F}(\mathrm{e}^+,\nu)^{17}\mathrm{O}$ *and* $^{17}\mathrm{O}(\mathrm{p},\alpha)^{14}\mathrm{N}$ *calculated for different temperatures* ($\rho = 10 g/cm^3$)

T_9, K	Cross section	Leng1	Leng2	F.C.Z.	Brown
0.015	< b1617 >	.63408E-19	.43151E-21	.98793E-19	.10303E-18
	< b1714 >	.13124E-19	.10548E-19	.11682E-17	.12159E-18
0.020	< b1617 >	.25512E-16	.16660E-18	.39051E-16	.40727E-16
	< b1714 >	.56995E-17	.43067E-17	.47341E-15	.10322E-14
0.025	< b1617 >	.18055E-14	.11419E-16	.27169E-14	.28342E-14
	< b1714 >	.43159E-15	.30791E-15	.33675E-13	.15590E-11
0.030	< b1617 >	.46314E-13	.28537E-15	.68549E-13	.71536E-13
	< b1714 >	.11772E-13	.79592E-14	.86717E-12	.22862E-09
0.035	< b1617 >	.61610E-12	.37132E-14	.89731E-12	.93677E-12
	< b1714 >	.16572E-12	.10653E-12	.11571E-10	.54472E-08
0.040	< b1617 >	.51981E-11	.30735E-13	.74520E-11	.77831E-11
	< b1714 >	.14738E-11	.90331E-12	.97877E-10	.53816E-07
0.045	< b1617 >	.31469E-10	.18295E-12	.44419E-10	.46413E-10
	< b1714 >	.93739E-11	.54923E-11	.59380E-09	.42650E-06
0.050	< b1617 >	.14817E-09	.84853E-12	.20598E-09	.21533E-09
	< b1714 >	.46241E-10	.25960E-10	.28011E-08	.19773E-05

Table 5: $^{16}\mathrm{O}/^{17}\mathrm{O}$ *isotope ratio in different objects*

Object	$X(^{16}\mathrm{O})/X(^{17}\mathrm{O})$	Reference
Sun	2700	Anders,Grevesse, 1989
	2600	Kameron, 1987
Solar system	2667	Harris, Lambert, 1987
Red giants	2700	Harris, Lambert, 1984a
	300–1000	Harris, Lambert. 1984b
	200–1000	Harris et al., 1988
MS,S and N stars	< 600	Harris et al., 1985

tem investigated indicate that the process of hydrogen burning, continuing for a long time, takes place at equilibrium values of concentrations ^{12}C, ^{13}C, ^{14}N and ^{15}N, which grow very slowly due to burning of ^{16}O (last three reactions of the CNO cycle, which we took into consideration). The nuclei of ^{14}N formed from oxygen are transformed instantaneously to equilibrium concentrations of the four isotopes mentioned above. Such a character of hydrogen burning process allows us to use equilibrium conditions for calculations of different stages.

At the initial stage we can write a system of equations for calculations of equilibrium concentrations of ^{12}C, ^{13}C, ^{14}N and ^{15}N.

$$\begin{aligned}
X(^{12}\mathrm{C}) = {} & (X_0(^{12}\mathrm{C})/12 + X_0(^{14}\mathrm{N})/14 + \\
& + X_0(^{13}\mathrm{C})/13 + X_0(^{15}\mathrm{N})/15)\cdot \\
& \cdot 12/(1 + < b1213 > / < b1314 > + \\
& + < b1213 > / < b1415 > + \\
& + < b1213 > / < b1512 >), \\
X(^{13}\mathrm{C}) = {} & X(^{12}\mathrm{C}) \cdot 13 \cdot < b1213 > / < b1314 >, \\
X(^{14}\mathrm{N}) = {} & X(^{12}\mathrm{C}) \cdot 14 \cdot < b1213 > / < b1415 >, \\
X(^{15}\mathrm{N}) = {} & X(^{12}\mathrm{C}) \cdot 15 \cdot < b1213 > / < b1512 >.
\end{aligned}$$

Then for each moment of time we calculate the quantity of ^{14}N produced from ^{16}O, and taking into account this change recalculate the equilibrium ratios of isotopes of the CN cycle. Just the same procedure (analogous set of equations) was used to calculate equilibrium ratios of isotopes in two chains of the CNO cycle (CN and NO). In this case we obtain additionally equilibrium concentrations of ^{16}O, ^{17}O and ^{17}F. Equilibrium in this chain is reached during a time comparable with the time of hydrogen burning and therefore this procedure can be used only to check the calculations.

8. Mass concentrations of elements

Values of changes of mass concentrations of nuclei are determined by the following set of equations:

$$dX(i)/dt = A_i(\pm\sum < bj > \cdot X(j)/A_j \pm \sum < b.j.k > \cdot X(j)/A_j \cdot X(k)/A_k,$$

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 on the right side is taken over all j for one–particle nuclear reactions, the second – over 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 stated, is determined by numerical integration over the time ($X_0(i)$ is the initial value of concentration):

$$X_T(i) = X_0(i) + \int_0^T dX(i)/dt \cdot dt.$$

We carried out a series of calculations of chemical composition changes as a result of operation of the CNO cycle. The interval of the used temperatures is $(15 - 50) \cdot 10^6$K, the interval of densities is $5 - 100$ g/cm^3. The original chemical composition is close to solar: 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 6, 7.

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 $\rho = 100\,\mathrm{g/cm^3}$) to 10^{13} years (for $T = 15 \cdot 10^6$ K and $\rho = 5\,\mathrm{g/cm^3}$). 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). So we can say that under certain conditions hydrogen burning requires much more time than the life time of our Universe.

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 8 and Fig. 4.

9. The structure of the primary in the period of formation of the observed chemical composition

The data from Tables 6–8 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.

The observed chemical composition of the primary of υ Sgr was formed, in our opinion, before the star 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. 5 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. 5. Thus for a star of 7 $M_\odot$ the parameters of the layer source must be close to the following: $T_1 = 40 \cdot 10^6$ 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 depth 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 and stimulates mixing. The dependence of the chemical composition of the core region upon the time (derived for $T = 180 \cdot 10^6 K$ and $\rho = 3.15 \cdot 10^3$ g/cm^3) is shown in Fig. 6. From this region additional carbon is supplied to the layer source of hydrogen burning.

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

Table 6: *The time (in sec) of entering the equilibrium hydrogen burning in CN cycle*

	T_9, K				
ρ,g/cm^3	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 7: *The time (in sec) of hydrogen burning in CN cycle up to X(H)=*$2 \cdot 10^{-2}$

	T_9, K				
ρ,g/cm^3	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}	$3 \cdot 10^{16}$	$3.5 \cdot 10^{13}$	$4 \cdot 10^{11}$	$4.5 \cdot 10^{10}$

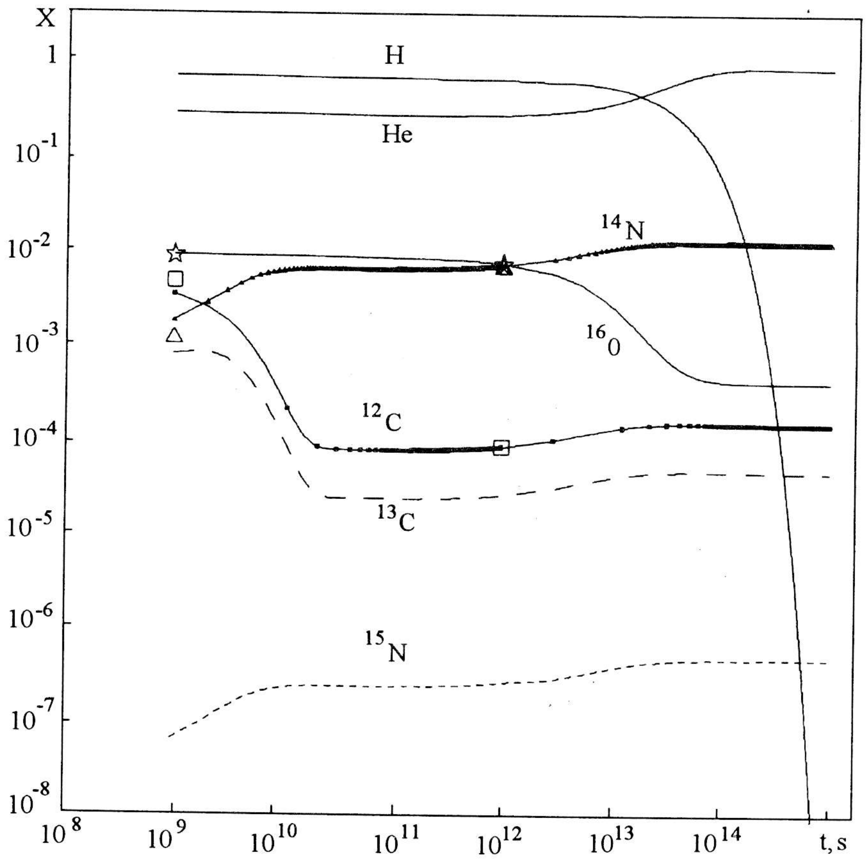

Figure 4: *Dynamics of nucleosynthesis in the star at* $T = 3 \cdot 10^6$ *K,* $\rho = 25$ *g/cm*^{3} *and initial chemical composition: X(H)=0.7, X(CNO)=0.015 before termination of hydrogen burning. The signs show the initial and equilibrium values of* ^{12}C, ^{14}N, ^{16}O *abundances.*

Table 8: *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

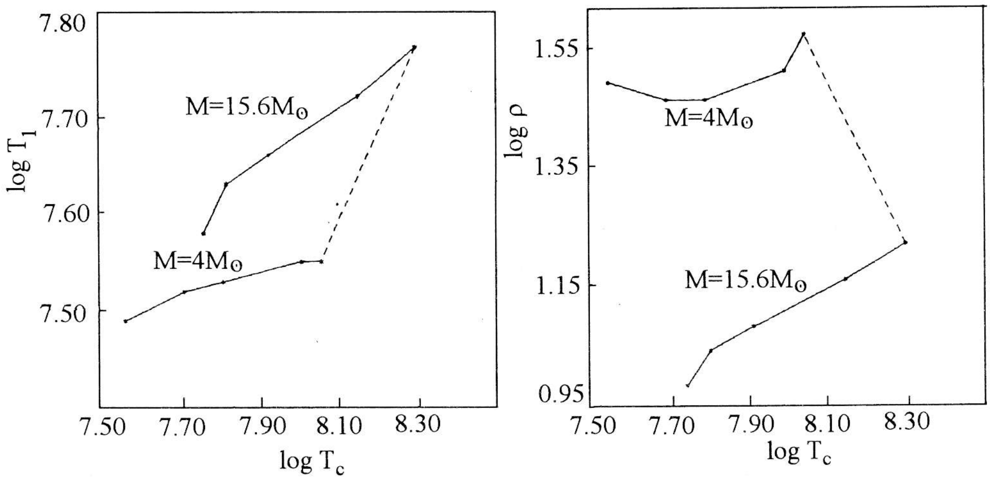

Figure 5: *Temperature T_1 and density ρ of the hydrogen shell source for stars of different masses as a function of temperature T_c at the centre (from calculations of Haiashi et al., 1962).*

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/cm^3. 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/cm^3.

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 depth 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.

The resultant 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 of υ Sgr. The chemical composition of the observed atmosphere of the primary is formed precisely in the considered period beneeth 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.

10. Chemical composition of different zones of the bright component of υ Sgr

The physical structure of the primary component in the stage of formation of the observed chemical com-

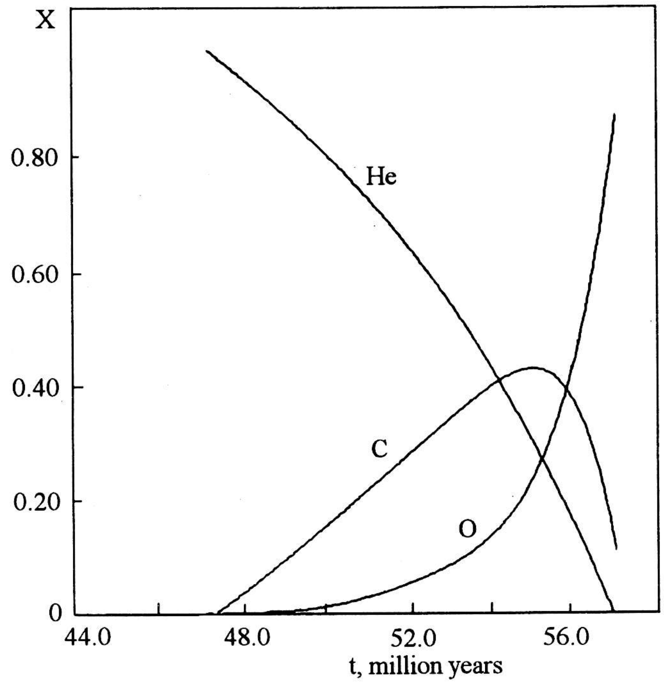

Figure 6: *Variation of chemical composition of the core region of the star with the temperature* $2 \cdot 10^8$ *K and* $\log\rho = 3.5$ *when carbon is synthesized from helium.*

position was responsible for the non–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. 6 for $T = 1.8 \cdot 10^8$ K and $\lg\rho = 3.5$. At these temperature and density values helium burns in the core of a star with $M = 7M_\odot$. The ratios between mass concentrations $X(\mathrm{He})/X(\mathrm{C})$ and $X(\mathrm{O})/X(\mathrm{C})$ for such a core, depending on time, are presented in Fig. 7. The nitrogen abundance in the core is constant and is within $X_0(\mathrm{N}) + X_0(\mathrm{C}) \leq X(\mathrm{N}) \leq X_0(\mathrm{N}) + X_0(\mathrm{C}) + X_0(\mathrm{O})$ 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.

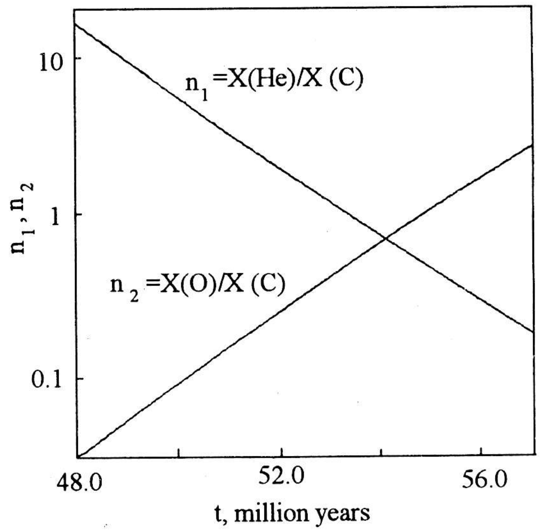

Figure 7: *He/C and O/C ratios as a function of time for the core region of a star of* $7M_\odot$.

1. 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 $Y = 0$).

2. 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.

3. 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.

4. 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.

5. The portion of matter dredged up from the helium burning zone (M_0) that is mixed with matter of the helium shell, is determined by the parameter $n_0 = M_0/M_2$.

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

1. Mixing of matter of the core and helium shell.
2. 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,
$X_0(\mathrm{O})$ – 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:
$X(\mathrm{He})_{env} = 1 - \mathrm{CNO}$,
$X(\mathrm{C})_{env} = 0$,
$X(\mathrm{N})_{env} = \mathrm{CNO} - X_0(\mathrm{O})$,
$X(\mathrm{O})_{env} = X_0(\mathrm{O})$.

The mass concentrations at the centre of the star:
$X(\mathrm{He})_{nuc} + X(\mathrm{C})_{nuc} + X(\mathrm{N})_{nuc} + X(\mathrm{O})_{nuc} = 1$,
$X(\mathrm{He})_{nuc} = n_1 X(\mathrm{C})_{nuc}$,
$X(\mathrm{C})_{nuc} = (1 - X(\mathrm{N})_{nuc})/(n_1 + n_2 + 1)$,
$X(\mathrm{N})_{nuc} = \mathrm{CNO} - X_0(\mathrm{O})$,
$X(\mathrm{O}))_{nuc} = n_2 X(\mathrm{C})_{nuc}$.

After mixing in the helium shell the chemical composition will be:
$X(\mathrm{He})_{env} = (1 - \mathrm{CNO} + n_0 X(\mathrm{He})_{nuc})/(1 + n_0)$,
$X(\mathrm{C})_{env} = n_0 X(\mathrm{C})_{nuc}/(n_0 + 1)$,
$X(\mathrm{N})_{env} = \mathrm{CNO} - X_0(\mathrm{O})$,
$X(\mathrm{O})_{env} = (X_0(\mathrm{O}) + n_0 X(\mathrm{O})_{nuc})/(1 - n_0)$.

In the core and in the shell it is sufficient to take into account only the main isophotes — ^{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:
$X(^1\mathrm{H}) = X(^1\mathrm{H})/(1 + n_3)$,
$X(^4\mathrm{He})_{layer} = (X(^4\mathrm{He}) + n_3 X(^4\mathrm{He})_{env})/(1 + n_3)$,
$X(^{12}\mathrm{C})_{layer} = (X(^{12}\mathrm{C}) + n_3 X(^{12}\mathrm{C})_{env})/(1 + n_3)$,
$X(^{13}\mathrm{C})_{layer} = X(^{13}\mathrm{C})/(1 + n_3)$,
$X(^{14}\mathrm{N})_{layer} = (X(^{14}\mathrm{N}) + n - 3X(^{14}\mathrm{N})_{env})/(1 + n_3)$,
$X(^{15}\mathrm{N})_{layer} = X(^{15}\mathrm{N})/(1 + n_3)$,
$X(^{16}\mathrm{O})_{layer} = (X(^{16}\mathrm{O}) + n_3 X_1(^{16}\mathrm{O})_{env}))/(1 + n_3)$,
$X(^{17}\mathrm{O})_{layer} = X(^{17}\mathrm{O}))/(1 + n_3)$.

Thus changing the input parameters n_0, n_1, n_3 and $X_0(\mathrm{O})$, one may change the rate and degree of mixing in different stages of helium burning in the core and hydrogen burning in the shell.

11. Calculation results

Using the above described model of chemical composition change in different zones of the star, we attempted to simulate the process of formation of the observed abundances of light elements in the atmosphere of the bright component of 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. According to the stated in Section 9, the structure of the investigated star can be presented as follows.

The carbon–oxygen core with a mass of 1.3 $M_\odot$ is surrounded by a helium envelope with a mass of 1.2 $M_\odot$. 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 of 4.5 $M_\odot$.

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 inhomogeneity in the core and the star as a whole to be preserved, we have considered the variants when 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 1. Besides, we varied the chemical composition of matter transferred from the helium burning zone ($n_1 = X(\mathrm{He})/X(\mathrm{C})$ and $n_2 = X(\mathrm{O})/X(\mathrm{C})$). 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. 7. These relations have been ob-

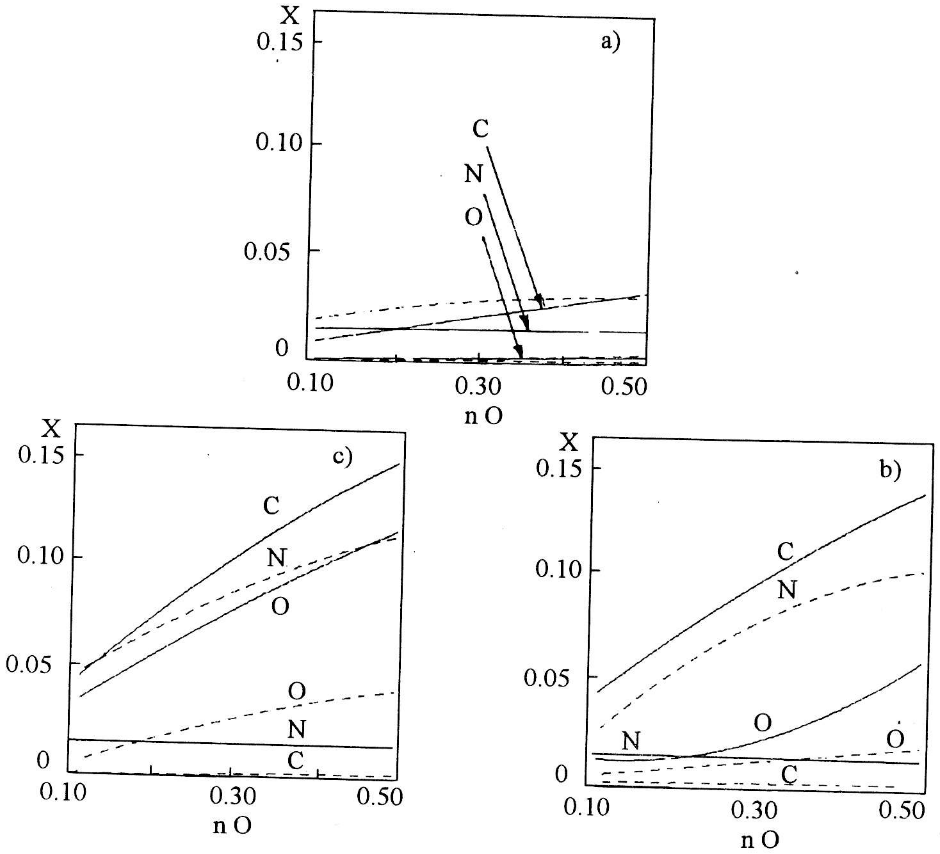

Figure 8: *Variation of chemical composition of the shell hydrogen source at the beginning (solid lines) and at the end (dashed lines) of hydrogen burning as a function of mixing parameter between the core and helium envelope (n_0). The results are given for the evolution stages corresponding to the ratios He/C in the core: a) He/C=10, b) He/C=1, c) He/C=0.5.*

tained from the calculation results of helium burning in the reactions

$$^4\text{He}(2\alpha,\gamma)^{12}\text{C} \text{ and } ^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$$

at a temperature $T = 1.8 \cdot 10^8$ and $\rho = 3.15 \cdot 10^3$ (the temperature and density correspond to a star with a mass of $M = 7M_\odot$ in the period of helium burning).

Variations in chemical composition of the hydrogen burning layer are presented in Fig. 8. Though there 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 9 shows the distributions of C, N and O 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 9 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.

12. Conclusions

A comparison of the C, N and O abundances observed in the atmosphere of υ Sgr ($X(\text{C}) = 0.012, X(\text{N}) = 0.043, X(\text{O}) = 0.008$) with the data from Table 9 shows that within the accuracy the observed values

Table 9: *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	n_1	n_0	n_4	C	N	O	C	N	O	C	N	O
1	1	0.2	0.5	0.068	0.015	0.028	0	0.056	0.007	0.021	0.043	0.017
2	2	0.2	0.07	0.050	0.015	0.010	0	0.045	0.002	0.004	0.043	0.00
3	2	0.25	0.25	0.060	0.015	0.013	0	0.050	0.003	0.012	0.043	0.005
4	2	0.026	0.33	0.062	0.015	0.013	0	0.052	0.004	0.015	0.043	0.006
5	2	0.27	0.4	0.065	0.015	0.014	0.001	0.054	0.004	0.018	0.043	0.007
6	2	0.3	0.5	0.07	0.015	0.015	0.001	0.057	0.004	0.023	0.043	0.007

are in good agreement with the theoretical, the fit being the best when

$X_e(\mathrm{C}) = 0.012, X_e(\mathrm{N}) = 0.043$
and $X_e(\mathrm{O}) = 0.005$,
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

$X_e(\mathrm{C}) = 0.015, X_e(\mathrm{N}) = 0.043$ and $X_e(\mathrm{O}) = 0.006$,

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 ($X(\mathrm{He})/X(\mathrm{C}) = 2$, $X(\mathrm{O})/X(\mathrm{C}) = 0.21$) 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 1/3 – 1/4 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.

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