THE MODERN EVOLUTIONARY STATUS OF THE BINARY WOLF-RAYET TYPE STARS

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The various modern evolutionary models for the binary Wolf-Rayet stars are considered. The evolutionary connection between various groups of binary *WR* stars is investigated. Proposed that *WR* stars with the *OVI* lines (*WR-OVI* stars) may be binary systems with compact components and *WN+WC* stars may be evolutionary transition objects between *WN* and *WC* stars.

1. Statement of the problem

After accumulation observational facts for the stars we must constrain physically reliable evolutionary models for these objects. Various models have been proposed for the understanding formation and evolution of Galactic Wolf-Rayet (*WR*) stars of population I, depending on the initial mass, chemical composition and binarity. In this paper we considered the models evolution of binary *WR* stars which are sufficiently verified with the observations and theoretical investigations. The evolutionary connection between various groups of binary *WR* stars is investigated.

In fact we know:

a) binary WR stars: *WR* stars with *O* components, *WR* stars with compact components – neutron stars or black holes, *WR* stars with mixing subtypes – *WN+WC* stars;

b) single *WR* stars.

Therefore we must explain origin and evolution of binary and single *WR* stars and evolutionary connection between different group of *WR* stars.

2. Formation and evolution of binary *WR* stars

In this section the evolutionary properties of close binary system and formation binary *WR* stars in this system are considered. It is known that a large part of the stars of the galactic disk are binaries. It is also known that progenitors of WR stars are massive *O* stars locating in the galactic disk. According to [1] 36% of the *O* stars are binaries. During the evolution the components of the close binary system can fill their Roche volumes, and lose mass in order to keep the star within the allowed surface. *WR* phenomena are observed namely when sufficiently mass loss takes place. The mass overflow via Roche surface and mass loss by stellar wind makes binary systems more convenient for the formation *WR* properties. Formation and evolution of *WR* stars in binary systems have been investigated in [2, 3, 4]. According to this investigations evolution massive close binary systems take place following way:

$$O_1 + O_2 \rightarrow WR_1 + O_2 \rightarrow c + O_2 \rightarrow c + WR_2 \qquad (1)$$

The evolution of the stars in binary systems is different from the evolution of a single star with the same mass and chemical composition. It is known that progenitors of the binary *WR* systems are massive close binary O_1+O_2 systems with a circular orbit. The O_1+O_2 system is called massive if at least one of its components will explode as *SN* and becomes to neutron star or a black hole. The O_1+O_2 system is called close binary if the period of this system is small enough that during evolution one or both components will fill the Roche lobe (Roche surface) – the critical equipotential surface of the star**.** The equipotential surfaces of components are crosses at first Lagrangian point *L1*, which is the point of gravitational balance between two components. Effective gravity is zero in point *L1* and matter can flow from one component towards the other. Process in which the star fills its Roche lobe and starts losing mass trough *L1* is called Roche lobe overflow - *RLOF*. The component losing mass due to *RLOF* is a mass loser, and the component that accepts matter is a mass accretor.

According to (1) in massive close binary system O_1+O_2 initially higher mass component (O_1) evolves more rapidly and system becomes to WR_1+O_2 and further WR_1 star in this system explodes as supernova (*SN*) and WR_1+O_2 system converts into $c+O_2$ where c is compact star (*c*- neutron star or black hole). The probability that the binary system remains bound is high, since the less massive star explodes [5]. From the evolutionary model (1) we may conclude that if the *SN* explosion does not disrupt the system the *WR* phase can appear twice, the first as *WR+O* system, the second as *WR+c* system. Another infer from (1) is that the number of *WR+c* systems might be expected to be similar to that of *WR+O* systems. Establishment the binary nature of *WR+c* stars from the spectral and photometric observations is very difficult because small amplitude of light and radial velocity (*RV*) variations. For the verifying theories on the formation of *WR* stars is important to determine what fraction of the *WR* stars are truly single. With the aid of model (1) we also can explain formation of $c+O_2$ system (*O* stars with compact components). *WR+c* and *c+O* type binary systems are called runaway stars because their location at high distances from the galactic disc.

As long as the radii of components of binary system O_1+O_2 are smaller than their Roche radius the system is detached system – only weak interactions can occur, i.e. interactions by tides, radiation, stellar winds, magnetic forces. For a given binary system, the Roche radius determined by the masses of the components and orbital period can be calculated. When one of the components (beginning more massive component) of the binary system during its evolution expands so that it fills its Roche surface (the stellar radius exceeds the Roche radius), mass transfer through the vicinity of the inner Lagrangian point (*L1*) starts. The binary system becomes too semi-detached. In semi detached systems the primary (more massive component) can lose of its initial mass sufficiently that is important for the formation of *WR* stars.

If the mass ratio of the components is near to 1 the two components can evolve simultaneously, while one component fills its Roche surface and loses matter, the another component can also expand and fill its Roche surface. In this case a contact binary is formed. The system can rotate as a solid body. The common surface can reach the outer Lagrangian point (L2), and mass loss through the vicinity of this point can occur. From this discussion it is obvious that the binary systems with the mass ratios less than 1 are convenient for the formation of the binary *WR* stars**.** Namely these systems become semi- detached and losses sufficiently mass that is necessary for the formation of *WR* stars.

Evolution of the stars in a massive close binary systems is strongly depends from the mass loss via *RLOF*. More massive component of the binary system is called primary. When the primary fills its Roche lobe, mass transfer starts. The gas on the surface of the primary will flow through the first Lagrangian point *L1* to the component. Depending on an initial period and masses in binary system, primary star can fill its Roche lobe:

1. core hydrogen burning phase - case *A*,
2. shell hydrogen burning phase - case *B* (the most frequent case),
3. shell helium burning phase - case *C*

When the Roche surface overflow phase ends, the remnant of the primary becomes to helium star. It is assumed that the accreting secondary evolves like a normal main sequence star. As a consequence of the rapid mass transfer the secondary can also expand and fill its Roche lobe. In this case contact system is formed, and the two stars have a common envelope. Namely in the case mass loss starts during core hydrogen burning the contact system forms. In the case mass transfer starts during shell hydrogen burning, it is easier to avoid contact phase. Therefore the binary systems where stellar radius increases during shell hydrogen burning or core helium burning are more convenient for the formation of binary *WR* stars.

Most model computations for the evolution of close binary stars were made under conservative assumptions, i.e. it is proposed that the total mass and the orbital angular momentum of the system are conserved during the mass transfer phase [6,7]. The conservative evolutionary computations lead only to a rough correspondence between observed and calculated parameters because factual loosing total mass and angular momentum by system. It is not very difficult to take into account mass and angular momentum losses from the system. Only a fraction β of the mass lost by the primary is accreted by the secondary, and also that a fraction γ of the total angular momentum is taken away by the matter leaving the system. This type of investigations is important for the obtaining real results which may be verifying by the observations.

_WR_ stars with _O_ components: _WR+O_ stars

The presence the absorption lines in the spectrum of some *WR* stars, the light and *RV* variations led astronomers to suggest *O* components for these stars. In 1939 for the first time was discovered the *WR* spectroscopic binary *V*444 *Cyg* [8]. For the being time we know many binary *WR+O* stars. According to modern evolutionary theories of close binary systems progenitors these systems are massive O_1+O_2 systems (see evolutionary model (1)). As noted above more massive component in binary system O_1+O_2 due to mass loss via *RLOF* and by stellar wind becomes to *WR* star.

In the seventies it was observationally confirmed that the absorption lines could originate in the *WR* star as well [9]. According to authors [10, 11] many of the *WR* stars with absorption lines are single. Therefore the *WR* stars can be called binaries only if light and *RV* variations was discovered. Since the discovery of *WR* stars, the problem of duplicity among *WR* stars has been a major one. Several years ago all *WR* stars were believed to be components of close binary systems. Therefore one of the important question concerning *WR* stars was whether all of them are members of close binary systems or single *WR* stars are also exist. Discovery the binary nature of *WR* stars is actual due to two reasons: first, for the understanding the role of the component in the formation of a *WR* star; second, the difficulty to determine the binary nature of the *WR* stars due to the widths of the spectral lines and low amplitude of the light and *RV* variations. After the discovery of *WR* binaries with compact components, we may estimate the real number binary *WR* stars. According to [12] 25% of *WR* stars are *WR+O* binaries. According to evolutionary model (1) the number *WR+O* system must be same with the number of *WR+c* ones. Therefore after to take into account the number of *WR* stars with compact components the percentage of binary *WR*'s increases up to 50%.

The study of *WR+O* binaries is important for the determination masses of WR stars. By measuring the velocities of both components in a *WR+O* system, we can determine the minimum masses and mass ratio of the two stars; if we can get some information about orbital inclination, we may calculate the masses of the *WR* stars. The determination of masses of *WR* stars in binary systems is complicated by two factors: a) uncertainties in the value of orbital inclination b) the errors in the determination velocity semi-amplitude. However, the mass ratio of the component of binary system may be determined correctly.

Observational properties some *WR+O* systems are investigated in [13]. The *WR* binaries in which the absorption spectrum of the *O* component is present and moves in the opposite sense than the *WR* emission lines denotes as *SB*2. In a some cases, the *WR* star is sufficiently brighter than its component that the spectra of *O* component is not present in the visible region, although the mass function of these systems implies with the presence of the massive component. Such *WR* binary systems denotes as *SB*1. Most of the *WR* binaries with massive components are *SB*2.

The masses of *WR* stars span a very large range: the mass of WR component of *CX Cep* is 11 M_O and the mass of *WR* component of *HDE* 311843 is 40 M_O. According to [14] the minimum masses of *WR* stars were strongly correlated with the mass ratios; stars with smaller masses were found in systems with smaller M_{WR}/M_O values. It is interesting that there are not correlation between *WN* and *WC* types and masses, though the mass ratios of *WR* binaries are correlated with types [15]. It is also interesting that the *WC* stars are not, in general, less massive than the *WN* stars. The reason may be that either not all *WN* stars become *WC* stars, or low mass *WC* stars are shorter lived than massive ones [16].

Another interesting problem is to determine the minimum mass that an *O* star must lose in order to be identified as a *WR* star. By extrapolation the current masses of the *WR* type components we may approximately determine the beginning mass of the *O* star. For the *WR+O* systems mass ratios approximately less than 0.6. Since the initial mass ratio of

O+O systems are nearly unity. From this we may infer that the *WR* components in binaries have lost at least 40% of their initial mass.

According to scenario Conti [17], a single *O* star will turn into a single *WR* star by stellar wind mass loss, while a binary *O+O* system will turn into a binary *WR+O* system by wind mass loss and mass loss via Roche surface. In this case are interesting: a) relative importance of wind mass loss and mass loss via Roshe surface b) what fraction of mass is accreted by the component?

It is interesting to compare the orbital eccentricities of the *O+O* and *WR+O* systems. All the *WR* stars with massive components have circular orbits except γ Vel (*e*=0.40), *HD*190918 (*e*= 0.43) and *HD* 92740 ($e \approx 0.6$). The longest period *WR+O* system with a circular orbit is *CV* Ser ($P \approx 30$ days). Most of the *O* stars with periods below 30 days have circular orbits. All the long period systems have non-circular orbits. In short period systems tidal interactions will circularize an orbit. If mass transfer has played a dominant role we might expect for the longer period systems to have circular orbits as well, since this is a consequence of mass transfer [18].

In some cases *WR* stars are member of eclipsing binary systems: *V*444 *Cyg*, *CX Cep*, *CQ Cep*, and *CV Ser*. Investigation of light curves of this eclipsing *WR+O* binary systems give us important information about physical characteristics of the *WR* stars that is necessary for understanding of their nature and evolution.

***WR+WR* binaries:**

Besides the *WR+O* systems there are some binary systems in which both members are *WR* stars (*WN+WC* stars). These stars have spectroscopic properties intermediate between *WN* and *WC* stars. It is known that the spectra of the most *WN* stars do not contain carbon, only lines of *CIV*$\lambda\lambda$5801 in the optical region and *CIV*$\lambda\lambda$1550 in the *UV* is observed. However strongest *CIII* lines (*CIII*λ4650 and *CIII*λ5696) are not generally observed in *WN* stars. If these lines are seen, the star is given subtype *WN+WC*, as if two stars were present. Although this does not mean that two separate stars are present. For the establishment the binary nature such systems *RV* and light variation investigations were need. Our photometric observations revealed light variation one of the *WN+WC* stars *AS*422=*MR*111 with the period 20^d [19].

The theory of the evolution of close binary stars predicts that *WN+WC* binaries might exist. The existence of such transition nitrogen-carbon stars indicate also an evolutionary connection between *WN* and *WC* stars. When *CNO* cycle approaches to the end and helium burning will begin and the carbon should manifest itself in the composition of the star. To produce *WR+WR* system the O star in a *WR+O* system must evolve into a *WR* during the lifetime of the other *WR* star. It is known that the lifetime of a *WR* stars is typically 10% of its *O* star life. Therefore the number of *WN+WC* systems must be small.

Investigation *WN+WC* system is very important for the understanding nature of *WR* phenomenon.

***WR* stars with compact components: *WR+c* stars**

The discovery of *OB* binary *X*– ray sources was important for understanding of massive binary star evolution with mass exchange and mass loss. One of the important conclusion from this was the prediction of the second *WR* binary phase (*WR+c*) in the evolution of massive binaries in which the component of the *WR* star is a neutron star of mass 1-2 M_O, or in some cases even more massive black hole [20].

The first observational fact that *WR+c* stars do exist to become clear from a study of the distribution (*z* distribution) perpendicular to the galactic plane of galactic *WR* stars for which distances was known. It was supposed that the *SN* explosion in a binary system has 'kicked' these stars out of the galactic plane and that they could be binary systems with the neutron-star component. Therefore *WR+c* stars must situate far from the galactic plane. It is found that single line *WR* stars (the *WR* stars presumed as single) tend to lie further from the galactic plane in the mean than double-line (presumed *WR+OB* binary) stars, which behave like normal population I of the galaxy. For a limited number within 6 kpc and *v*<12mag for which the duplicity was reliable determined, found $|z|$ =133 pc for single-line and 79 pc for double-line *WR* stars (*z* is distant from the galactic plane) [21]. From this concluded that, among the single-line stars, there exist a significant number *WR+c* stars. Among the *O* stars also there are runaway stars i.e. stars situated far from the galactic plane. This fact interpreted analogously runaway *WR* stars.

The next reasonable step would be photometric and spectral observations (for the revealing possible radial velocity, line profile, light variations) of individual *WR* stars for the establishment their duplicity. The spectral and photometric detection the duplicity of *WR+c* stars is very difficult because the radial velocity and light variations are very low. Spectral detection of duplicity more comfortable for the narrow line *WNL* (*WN*6-8) stars. A necessary minimum requirement is a reliable measure of the *RV* semi-amplitude of the *WR* component, which leads to an estimate of the mass of the compact component, after assuming a mass for the WR stars and the orbital inclination. If the masses of the secondary is in the range ~ 1-2 M_O, it could be a neutron star; if more than ~3 M_O a black hole component. Additional observational prove would come from the investigation phase dependent line profile variations.

he spectral and photometric searching for the duplicity among the *WR* stars with high probability of finding WR + c systems; e.g. single-line *WR* stars with high $|z|$ in the galaxy, surrounded by a ring nebula (ejected during the during rapid mass transfer from the pre-*WR* star to the component) lead to detection of *WR+c* stars. Presumably, many more *WR+c* stars remain to be detected.

The low mass-function for the *WR+c* stars indicate for the compact components mass ~0.5-2M_O in most cases, compatible with the presence of neutron star (*NS*) component. We thus assume 1.6 M_O, an appropriate mean value for *NS* in *X* ray binaries [22], in order to derive the *WR* star masses.

HD 197406 is more probably *WR+Black* Hole. The distance from the galactic plane for the *HD* 197406 is 799 pc because this star is called the extreme runaway. Obtained that the mass of compact component in *HD* 197406 is ~14 M_O . The light curve of this star shows a shallow dip of ~ 0.04mag.

Beside orbital motion, there are other physical processes which could produce the observed low-amplitude, periodic *RV* and light variations. One of them is pulsation of the star. It is known that massive He burning stars as identified with the late *WN*(*WN*6-8) and *WC* stars have radial pulsation periods in the range of 30 min [23].This period much shorter than any periods observed in *WR+c* systems. Another reason of observed periodic variations may be also rotation. Rotation of the star associated with the surface inhomogeneities (may be associated with the magnetic field) might give periodic variations. However following observational facts make more probably that observed periodic variation is due to presence compact component of the *WR* star:

1. location at high z distance from the galactic plane
2. the presence ring nebulae around star

<u>*WR* stars with the enhanced lines of *OVI*: *WR–OVI* stars</u>

Another interesting group of stars is Pop. I *WR* stars whose optical spectra display the emission doublet *OVI*$\lambda\lambda$3811, 3834. These stars are called *WR – OVI* stars [24]. According to our investigations at least some of these stars may be close binary systems with the probable compact components. We revealed following observational facts in favor this assumption:

a) similar *z* distribution of *WR* stars with *OVI*$\lambda\lambda$3811, 3834 lines and *WR* stars with the probable compact components
b) rapid spectral variability of some spectral lines in the spectra of the *WR-OVI* stars; such a rapid spectral variability is characteristic for the *WR + c* stars [25]
c) considerable scattering in the dependence 'emission line widths – ionization potential' and uncertainty of spectral subtypes as estimated from the different criteria. These effects may be due to compact objects which are components of the *WR–OVI* stars [26].
d) the observation of the ring nebulae around some *WR–OVI* stars. Such ring nebulae are observed also around *WR+c* stars [27].
e) the discovery of the periodic variability of the light and radial velocity of the *WR–OVI* star *HD* 16523 [24]

3. The probable evolutionary connections between different group of binary *WR* stars

It is known that *WR* stars have been divided into three spectral types: the *WN*, *WC* and *WO*. It is suggested that the separation of *WR* stars to types is connected with the different chemical composition and related to stellar evolution [24]. We know *WN+O*, *WC+O*, *WO+O* systems. Progenitors of these systems are massive close binary O_1+O_2 systems. Therefore the evolutionary model (1) may be written in following form:

$$\begin{array}{ccccccccccc} & & & & WN+O_2 & & & & & & \\ & & & & \downarrow & & & & & & c+WN \\ O_1+O_2 & \rightarrow & Of/WN+O_2 & \rightarrow & WC+O_2 & \rightarrow & c+O_2 & \rightarrow & c+Of/WN & \rightarrow & c+WC \\ & & & & \downarrow & & & & & & c+WO \\ & & & & WO+O_2 & & & & & & \end{array} \qquad (2)$$

As noted above the evolution of the stars in a massive close binary systems is strongly depends from the mass loss via *RLOF*. For a given binary system, the Roche radius depends from the masses of the component and orbital period**.** Therefore *RLOF* also depends from the mass ratio of the component. We suggest that formation *WN+O*, *WC+O* or *WO+O* systems from O_1+O_2 system depend from mass ratio in binary O_1+O_2. As noted above the mass ratios of *WR* binaries are correlated with types *WN* and *WC*. This observational fact is favor to our suggestion. According to [24] there is such evolutionary connection between *WN*, *WC* and *WO* types:

$$WN \rightarrow WC \rightarrow WO \qquad (3)$$

There is analogous evolutionary connection between *WN+O*, *WC+O* and *WO+O* binaries. In evolutionary model (2) we show arrows between these systems indicating probable evolutionary connection.

We suggest that transition from O_1+O_2 to $WR+O_2$ system also depends from that at what stage takes phase *RLOF* in binary system O_1+O_2. If *RLOF* takes place at core hydrogen burning phase (case *A*) formation of *WN+O* system more probable. If *RLOF* takes place at shell helium burning phase then (case *C*) the formation of *WC+O* and *WO+O* systems more probable.

It is known that there are evolutionary transition objects (*Of/WN*) between *O* and *WN* stars. Therefore must be evolutionary transition binary $Of/WN+O_2$ systems (quasi WR binaries) between O_1+O_2 and $WR+O_2$ type binaries. We also proposed that there are evolutionary transitional *c+Of/WN* objects between *c+O* and *c+WR* stars.

The evolutionary model (2) prorosed by us for the first time and is more detailed than model (1).

4. Main conclusions:

1. Progenitors of binary *WR* systems are massive close binary O_1+O_2 stars.
2. The masses of *WR* stars span a larger range than do their *O* type components. The average mass of a *WR* star is about $20M_O$.
3. The masses of *WC* stars are not less than those of *WN* stars.
4. The mass ratios of *WR+O* binaries are correlated with the types *WN* and *WC*.
5. *WR* stars in binaries have lost at least 40% their mass in becoming *WR* stars.
6. The short period *WR+O* systems have circular orbits, identical to what is know for the O_1+O_2 systems.
7. Some *WR-OVI* stars may have compact components.
8. *WN+WC* stars may be in the intermediate position of the evolution from *WN* to *WC* stars.

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QOŞA VOLF-RAYE TİPLİ ULDUZLARIN MÜASİR TƏKAMÜL STATUSU

Qoşa Volf-Raye ulduzların müasir təkamül modellərinə baxılmışdır. Müxtəlif qrupa daxil olan qoşa WR ulduzları arasında təkamül əlaqələri tədqiq olunmuşdur. OVI xətləri olan *WR* ulduzların (*WR - OVI* ulduzlarının) kompakt komponentləri olan qoşa sistemlər ola bilməsi fikri irəli sürülmüşdür. Ola bilsin ki, *WN + WC* ulduzları təkamülcə *WN* və *WC* ulduzları arasında keçid obyektləridir.

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СОВРЕМЕННЫЙ ЭВОЛЮЦИОННЫЙ СТАТУС ДВОЙНЫХ ЗВЕЗД ТИПА ВОЛЬФА-РАЙЕ

Рассмотрены различные современные эволюционные модели для звезд Вольфа-Райе. Были исследованы эволюционные связи между различными группами двойных звезд *WR*. Предположено, что звезды Вольфа-Райе с линиями *OVI* (звезды *WR - OVI)* могут являться двойными системами с компактными компонентами. Звезды *WN + WC* могут являться эволюционно переходными объектами между *WN* и *WC* звездами.

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