STATISTICS OF WOLF-RAYET BINARIES

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ABSTRACT. A theoretical model of the ensemble of galactic Wolf-Rayet stars is constructed, assuming that all of them are members of either close or wide binaries. The model provides a reasonable explanation of the observed number of WR stars, their distribution over masses, mass ratios of components in binary systems, and spatial velocities. It predicts that up to 10 % of the apparently single WR stars have relativistic companions hidden inside thick stellar winds.

1. The Model

In this contribution we discuss some results pertaining to Wolf-Rayet (WR) stars, obtained by a numerical code, by means of which we attempt to model the binary star population of the Galaxy.

The essence of the method applied is the following. It is assumed that all stars are binaries, either close or wide. From the statistical studies of binary stars one may infer the following equation for the birthrate of binaries (Popova *et al.*, 1982):

$$d^3\nu \approx 0.2 d\log A \; M_1^{-2.5} dM_1 \; f(q) dq$$

where $1 < \log(A/R_\odot) < 6$ is the major semiaxis of the orbit, $0.8M_\odot < M_1 < 100M_\odot$ is the mass of primary component, $q = M_2/M_1$ is the mass ratio of components. The normalization constant corresponds to the formation of about one white dwarf per year in the Galaxy.

Concerning the q-distribution function $f(q)$, one may assume that $f(q) \propto q^\alpha$. There are arguments both for a "flat" ($\alpha = 0$) distribution (Kraicheva *et al.*, 1990) and for a distribution inversely proportional ($\alpha = -1$) to q (Trimble, 1990). We have performed computations both for $\alpha = 0$ and -1.

The evolution of both wide and close binaries is completely determined by their initial M_1, M_2, A. Therefore one may choose a fixed point in the phase space of these parameters to follow all evolutionary transformations experienced by a binary with given M_1, M_2, A. The product of the birthrate of stars with a certain set of initial parameters and of a lifetime in any particular stage of evolution then gives the number of stars in this stage. Simultaneously one obtains all physical characteristics of the binary. Exploring numerically the whole phase space of parameters, one obtains the total numbers of stars of particular types in the Galaxy. This approach in analytical form was successfully applied to cataclysmic

K. A. van der Hucht and B. Hidayat (eds.),
Wolf-Rayet Stars and Interrelations with Other Massive Stars in Galaxies, 459–464.

binaries, hot subdwarfs, supernovae, etc., in a series of papers by Iben and Tutukov and Tutukov and Yungelson.

The numerical code employing this approach (Tutukov and Yungelson, in preparation) accounts for such processes as mass exchange in close binaries, stellar wind mass loss, angular momentum and mass loss through common envelopes, magnetic braking, gravitational wave radiation, ejection of mass by supernovae and formation of black holes and neutron stars by them. For the masses of remnants after mass exchange or intense stellar wind mass loss stages and the lifetimes of stars we use the analytical approximations of results of evolutionary computations.

The most uncertain phenomenon in close binaries evolution is the mass and angular momentum loss. We treat it as follows. The donor loses ΔM_d of matter in its thermal time scale τ_d, but the companion accretes only a part of this matter ΔM_a in its own thermal time scale τ_a. Thus the efficiency of accretion is about $M_a/M_d \cdot \tau_d/\tau_a$. We split all mass exchange episodes into two phases. In the first one ΔM_a is exchanged and the distance A changes according to the usual conservative formalism. In the second one $(\Delta M_d - \Delta M_a)$ is lost from the system and A changes according to a common envelope formalism (Tutukov and Yungelson, 1979):

$$(M_a + M_d)(\Delta M_a - \Delta M_d)/A_o = \beta(M_a + \Delta M_a)(M_d - \Delta M_d)(1/A_f - 1/A_o)$$

with A_o and A_f being the initial and final separations, and $\beta(\approx 1)$ being a parameter describing the efficiency of orbital energy expenditure on common envelope ejection. Stars with deep convective envelopes were assumed to have only a nonconservative phase of evolution, because of the short time scale of mass exchange episodes.

Stars with initial mass $10 < (M/M_\odot) < 30$ were assumed to produce $1.4M_\odot$ neutron stars, initially more massive stars were assumed to produce $5M_\odot$ black holes.

The initial spatial velocities of stars were estimated under assumption of equipartition of their kinetic energy: $M_1 v_r^2 = 2000 M_\odot (km/s)^2$. Additional components to these velocities are provided by supernovae explosions. The modulus of the resulting velocity is $v = (v_r^2 + v_{SN}^2)^{0.5}$.

Earlier modelling of the ensemble of galactic WR stars assuming that all of them are close binaries has been attempted by Doom and De Greve (1982).

2. The Results

According to current ideas WR stars are core helium burning remnants of initially more massive stars, which have lost their hydrogen envelopes by mass exchange in close binaries (Paczynski, 1967) or by stellar wind (Conti, 1976). If the initial masses of WR stars exceed $10M_\odot$, then their predecessors in close binaries were more massive than $\sim 25M_\odot$. We also assume that components with mass exceeding $50M_\odot$ lose their hydrogen envelopes by stellar wind in the main-sequence stage, both in close and wide pairs. They become WR stars immediately after the main-sequence stage. The separations in this case were changed adiabatically: $(M_1 + M_2) \cdot A = constant$. A strong argument in favour of this picture provides the coincidence of the spatial distribution of WR stars with that of apparently single OB stars with $M/M_\odot > 40 - 50$ (Conti *et al.*, 1983) and of close binaries with $M_{1,2} > 25M_\odot$ (Tutukov and Yungelson, 1985).

Our code generates several scenario's in which bare core helium burning stars more massive than $10M_\odot$ appear. The distribution of numbers of different types of systems containing WR stars is shown in Table 1. The Table displays estimates obtained for two initial distributions over q ($\alpha = 0$ and -1) and for minimum masses of WR stars equal to 8 and $10M_\odot$, as well as some numbers pertaining to observed stars.

Table 1. Statistics of galactic Wolf-Rayet Stars

	TOT.	WR+MS	WR+MS $A \leq 10^3 R_\odot$ $\lvert\Delta M_b\rvert \leq 1^m$	WR+NS	WR+BH	WR+WR	WR+SG	WR	TOT. $A \leq 10 R_\odot$	WR+REL $A \leq 10 R_\odot$
$AL=0$	1185	702	197	193	252	20	2	16	134	130
$M \geq 10 M_\odot$		59%	17%	16%	21%	1.7%	0.2%	1.4%	11%	11%
$AL=-1$	977	690	117	101	156	10	1	20	77	74
$M \geq 10 M_\odot$		71%	12%	10%	16%	1%	0.1%	2%	8%	8%
$AL=0$	1544	929	306							
$M \geq 8 M_\odot$		60%	19%							
OBS.	157	$v \leq 11^m$	$v \leq 17^m$	13?	3?	3				
		43%	14%	8%	2%	2%				

The total number of galactic WR stars is unknown. Van der Hucht *et al.* (1988) count 46 WR stars inside a 2.5 *kpc* circle around the Sun where the sample is complete. With the 12 *kpc* radius of the Galaxy this results in about 1000 stars in the whole volume. The model estimates for both $f(q)$ are close to this number. Most model WR stars have main-sequence (MS) companions. Among observed relatively bright ($V \leq 11^m$) WR stars the percentage of close binaries is high: $\sim$ 43%. In most observed double-line spectroscopic binaries with WR components the difference of visual magnitudes of components $|\Delta M_v| \leq 1^m$. Otherwise the secondary spectrum is not observed. If we pick from the model sample of WR stars only systems with the difference of bolometric magnitudes $|\Delta M_b| \leq 1^m$ (this is justified by the proximity of colour temperatures of WR and O stars) we obtain the rate of binarity 12% - 17% which is close to the overall observed value. If one limits the major semiaxes of orbits of model WR+MS systems by $1000 R_\odot$ as in the observed sample, the rate of binarity declines slightly more.

A part of the WR stars has unseen low mass companions, which we had predicted (Tutukov and Yungelson, 1973) to be neutron stars (NS) or black holes (BH). The theoretical relative frequency of them is 26 - 38%, the observed one about 10%. However, it is evident that a lot of low mass companions still have to be discovered.

Only a small portion of the WR stars are really single stars. These are merger products which have attained masses exceeding $50 M_\odot$. The secondaries of systems disrupted by the first SN explosion do not have high enough masses to produce WR stars.

The percentage of WR+WR systems as well as that of WR stars accompanied by supergiants (SG) is very low because such pairs arise only from wide pairs with very close initial masses of components.

About 10% of all WR stars have to have very close ($a \leq 10 R_\odot$, $P \leq 1$ day) companions. Almost all of them are neutron stars or black holes. Both components form a common envelope system inside the thick stellar wind of the WR star. Possibly they manifest themselves by some kind of periodical variability, that can be discovered by special ultraviolet observations.

About 40% of the model WR stars are descendants of stars that have lost their envelopes by stellar wind. This agrees well with the estimate based on the study of the spatial distribution of WR and O stars (Tutukov and Yungelson, 1985).

The mass distribution of all model WR stars is double-peaked (Fig. 1), in obvious contradiction to the mass function of WR stars in double-lined binaries (dots in Fig. 1

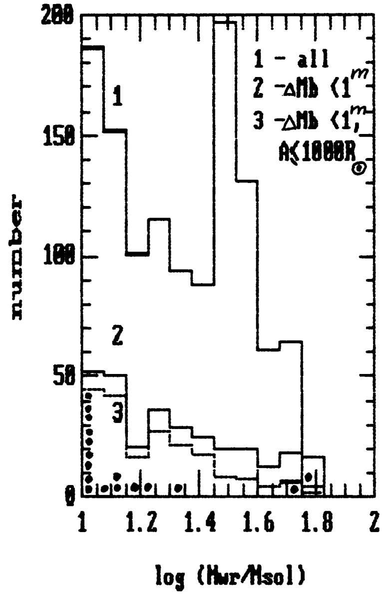

Fig. 1. Distribution of model WR stars over mass

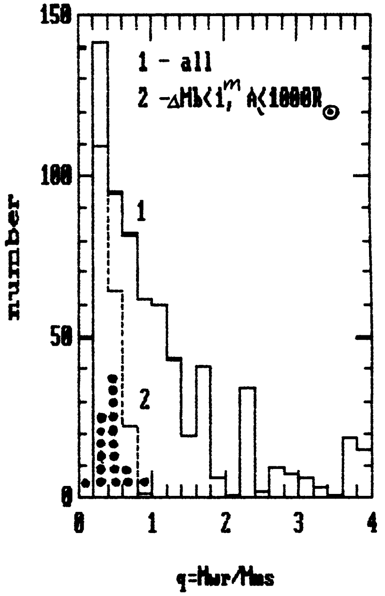

Fig. 2. Distribution of model WR stars over q

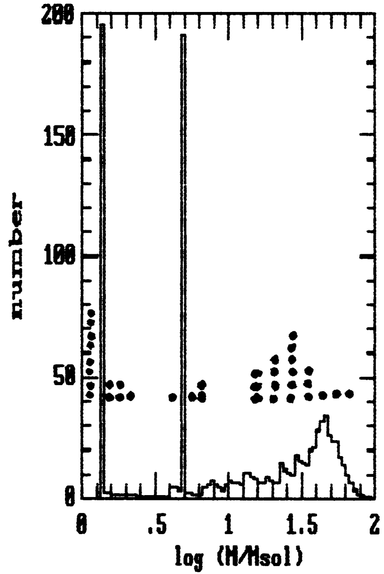

Fig. 3. Number - mass distribution of companions of WR stars

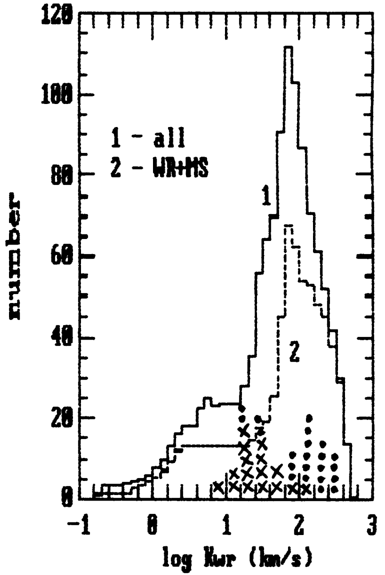

Fig. 4. Distribution of model WR stars over maximum Kwr

as well as in other Figures are related to observed stars (Aslanov *et al.*, 1989)). One may reduce the relative number of massive stars by lowering the minimum mass of WR stars to $\sim 8M_\odot$ or by increasing to $60-70M_\odot$ the lower mass limit of single stars that become WR stars. However, the discrepancy may be a mere result of observational selection. Limiting the model sample again by $|\Delta M_b| < 1^m$ and $A \leq 1000R_\odot$, one removes from it most of the massive stars (Fig. 1) and gets agreement with observations. The shape of the initial distribution over q influences the mass spectrum of WR stars only weakly, because most of them descend from initially primary components.

One of the most reliable observed parameters for WR+MS binaries is the mass ratio of the components (Fig. 2). A significant proportion of all model systems have $q > 1$. But by taking into account the same selection effects one gets reasonable agreement with observations.

No definite evidence of low mass companions of single-line observed WR stars being neutron stars or black holes does exist. In Fig. 3 we show the distribution of satellites of model WR stars over mass (for systems with a semi-amplitude of radial velocity $K_{WR} \geq 10\ km{\cdot}s^{-1}$ as in the observed sample. Three peaks of it are due to $1.4M_\odot$ neutron stars, $5M_\odot$ black holes and $(10-100)M_\odot$ OB stars. It is important to note that the overwhelming majority of companions with $M < 6M_\odot$ are relativistic stars. White dwarfs are absent and only a few companions are normal dwarfs.

Fig. 4 shows the distribution of all WR stars and WR stars with main-sequence companions over the maximum semi-amplitude of radial velocity K_{WR}. The relativistic companions in the systems with $10\ km{\cdot}s^{-1} \leq K_{WR} \leq 100\ km{\cdot}s^{-1}$ have to be predominantly neutron stars as it is also suggested by observational data (crosses: Aslanov *et al.*, 1989). The systems with $K_{WR} \geq 50\ km{\cdot}s^{-1}$ are probably immersed into common envelopes and still wait discovery. The theoretical ratio is $N_{NS}/N_{BH} \approx 0.57$ for $\alpha = o$ and ≈ 0.71 for $\alpha = -1$. The observed ratio is -4. This may indicate that we underestimate the lower mass limit for predecessors of black holes. However, more firm observations are necessary for definite conclusion. Positions of WR stars with MS-companions agree well with the observations (dots).

The first SN explosion in a close binary provides it with a high spatial velocity which it maintains in the second WR stage (Tutukov and Yungelson, 1973). The distribution of observed WR stars over the spatial velocities is unknown. However, the main-sequence lifetime of precursors of second generation WR stars is long enough to increase the scale-height of the whole subsystem of the galactic WR stars. Very roughly, the modulus of z-coordinate relates to spatial velocity as $|z|(pc) = 10v\ (km{\cdot}s^{-1})$. The ratio of the number of observed WR stars with $|z| > 100\ pc$ to the number of stars with $|z| < 100\ pc$ is close to 0.55. The predicted ratio of number of stars with $v > 10\ km{\cdot}s^{-1}$ to more slow ones is about the same, in reasonable agreement with observations.

3. Conclusion

The proposed model of evolution of galactic binaries assumes two channels for WR star formation - by mass exchange in close binaries and by stellar wind mass loss in both close and wide very massive binaries. The first channel produces about 60% of all WR stars, the second about 40%. This model, after taking into account some simple observational selection effects, satisfactorily describes the statistical properties of the observed ensemble of galactic WR stars.

Most WR stars with unseen companions have neutron star or black hole satellites, which are descendants of initial primaries.

About 10% of all WR stars may have very close ($A \leq 10R_{\odot}$) neutron star or black hole companions, immersed into their optically thick stellar winds.

The high spatial velocities of about 40% of the apparently single WR stars are a result of supernova explosions in close binary systems.

The change of the initial distribution of massive binaries over q from a flat one to one inversely proportional to q, does not influence the theoretical sample of WR stars strongly enough to discriminate between them on an observational basis. The main obstacle for this task is the proper account of observational selection.

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DISCUSSION

Vanbeveren: Your conclusions concerning the WR+c binary frequency very much depends on the adopted model for the mass transfer in close binaries. Could you comment on that?

Yungelson: We had adopted a model that allows to estimate the efficiency of accretion and to estimate the angular momentum loss through common envelopes. It predicts the periods and semi-amplitudes of the radial velocity distribution in a satisfactory agreement with observations. This may be considered as evidence of plausibility of the adopted model.