ON THE EVOLUTION OF WOLF-RAYET STARS IN CLOSE BINARY SYSTEMS

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ABSTRACT. The statistical study of the mass ratios of the components and eccentricities of close binary systems was made. Relations between these characteristics are obtained.

Results of the analysis allows to conclude that at least 70% of all known WR+O binary systems (with orbital period $P < 20^d$) where formed as a result of mass transfer in massive close binary systems.

Therefore, mass transfer through Roche lobe overflowing in massive close binary systems is an important mechanism of evolution in these interacting binaries.

Key words: Stars: binary: Wolf-Rayet.

1. Introduction

A good progress has been achieved in the understanding of the nature and evolution of Wolf-Rayet (WR) stars in close binary systems (Paczynski, 1973, Tutukov and Yungelson, 1973, Van den Heuvel and Heize, 1972). It is clear now that WR stars in close binaries can be considered as bare cores of initially more massive stars which lost up to 50phase of evolution (e.g. see the books of Shore et al., 1994 and Cherepashchuk et al., 1996 and references therein).

Recent increasing of observational data about WR stars in WR+O binary systems, especially, information on the masses of WR and O companions, allowed to suggest that mass transfer is insignificant, probably as a result of constantly present stellar winds and their collision in massive star close binaries, especially after the WR stage is reached for the primary component (e.g. Moffat, 1995).

Basic arguments for such a suggestion are the following:

1. There is no anticorrelation between masses of WR stars and O components in WR+O binaries, which could be suggested in the case of conservative mass exchange in massive close binaries. Moreover, some rough correlation between the masses of WR and O stars in WR+O binaries may be suggested (Cherepashchuk, 1991). Also, the mass of WR star decreases monotonically as one goes from cool to hot subtypes, whereas the mass of O companion is independent of the WR star subtype or its mass.

2. Among WR+O binaries there are systems with long periods, which have high values of eccentricity of the orbit, which can be considered as an argument against mass transfer (Massey, 1981). In this letter we compare the masses of companions in WR+O binaries with those of semi-detached close binary systems containing subgiants where mass transfer with no doubt occured. Also we compare the eccentricities of the orbits of WR+O binaries with those of detached and semi-detached close binary systems. For our investigation we use the data of Catalog of eclipsing binaries, containing data about 303 systems (Karetnikov and Andronov, 1989). We applie only photometrical values of the eccentricities of orbits which are much more reliable than spectroscopic. Results of the paper of Karetnikov and Cherepashchuk (1998) concerning statistical investigation of eclipsing binaries were used too.

2. Correlation between the masses of companion in WR+O and semi- detached close binaries with subgiants.

Dependence of the masses of WR stars MWR on the masses of O companion MO in WR+O binaries is presented on Fig.1a (the observational data are taken from Catalog of Cherepashchuk et al., 1996). Some rough correlation can be suggested in this case, but no anticorrelation exists.

Dependence between the masses of companions in semi-detached (SD) close binaries is presented in Fig.1b. There is clear correlation (but not anticorrelation) between the masses of M_1 and M_2 in semi-detached close binaries which went through Roche-Lobe overflowing mass transfer phase. In the paper of Karetnikov and Cherepashchuk (1998) this correlation was explained as a results of influence of initial conditions in the formation of close binaries. Average value of mass ratio in detached close to unity (~ 0.8, according to Karetnikov and Cherepashchuk, 1998). Mass exchange in semi-detached close binaries can not suppress

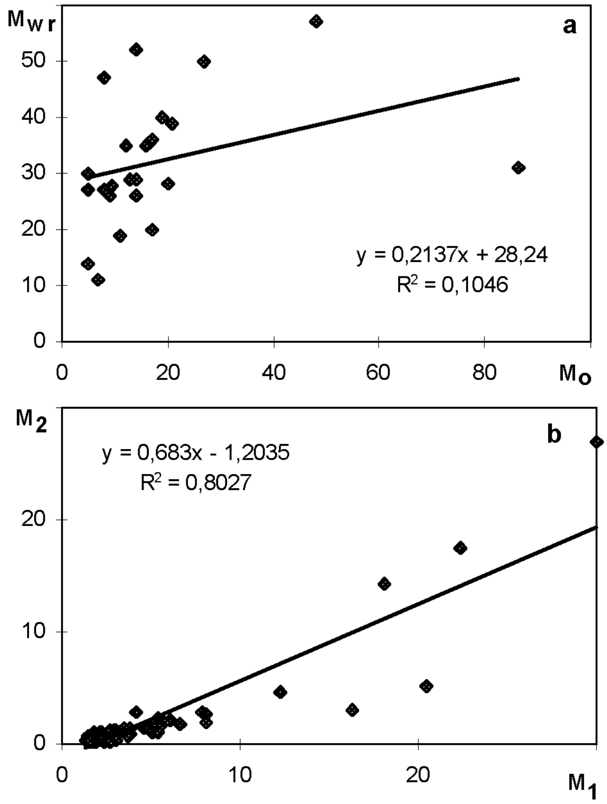

Figure 1: Dependence between stellar masses WR (a) and SD (b) binaries.

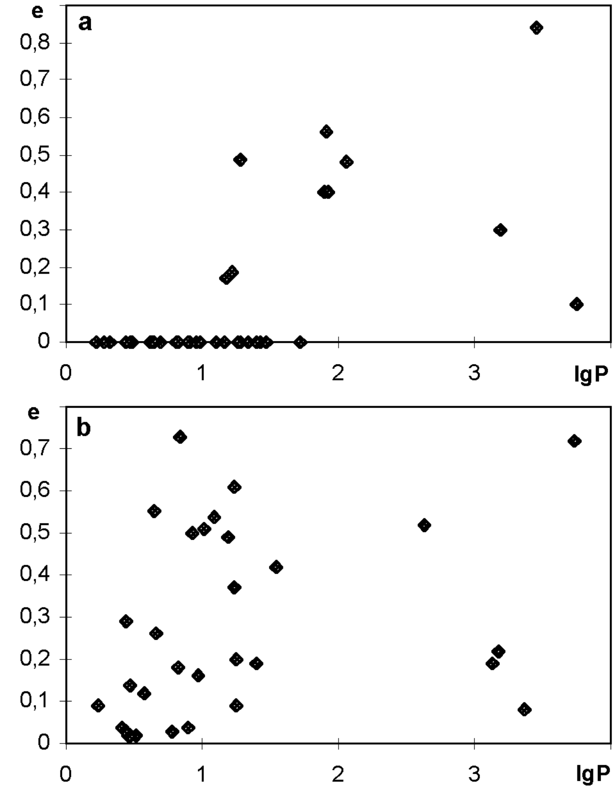

Figure 2: Dependence between stellar masses WR (a) and SD (b) binaries.

the influence of the initial condition for formation of close binaries.

Because there is no anticorrelation between the masses of the companions in semi-detached close binaries, absence of anticorrelation between masses of WR and O companions in WR+O binaries can not be considered as serious argument against mass transfer. Correlation between the masses of WR and O companions in WR+O binaries can be explained by influence of initial condition in the formation of massive close binary systems as well as by the fact that initial mass ratio is close to unity.

3. Comparison of the eccentricities of the orbits for WR+O binaries and detached and semi-detached binaries.

On the Fig.2a dependence of the eccentricities of the orbits e on the orbital periods P for WR+O binary systems is presented. For $P < 14^d$, $e = 0$ for all known WR+O binaries. On the Fig.2b dependence of $e(P)$ for all eclipsing binaries is presented. In this case $e = 0$ for $P < 2d$. For $P > 2d$, $e \neq 0$.

Therefore, for WR+O binaries $e = 0$ for much more higher values of orbital periods, up to 15 days is contrast to classical eclipsing binary systems. Among all known semi-detached eclipsing binaries with subgiants $e = 0$, which implies that mass transfer results in effective circularization of the orbits. Therefore, because in WR+O binaries $\sim 70\%$ systems have circular orbits, we can conclude that most of WR+O binaries were formed as a result of mass transfer in massive close binary systems. Only small parts of WR+O binaries ($< 30\%$) with longest orbital periods ($P > 14^d - 20^d$) may be formed without mass transfer mainly due to mass loss through stellar wind and wind-wind collision.

4. Examples of massive close binary system with mass transfer

Let us note some massive close binaries in which mass transfer is directly observed.

1. RY Sct: this massive O+O binary belongs to the well known W Ser type of close binary systems. Intensive mass transfer in this system occures and geometrically thick opaque disk around more massive companion is formed. This system may be considered as progenitor of WR+O binaries (Antokhina and Cherepashchuk, 1988).

2. SS 433: in this massive close binary containing relativistic object and Roche-Lobe filling optical star intensive secondary mass transfer occures in thermal

Table 1. Data of Close Binary with Wolf-Rayet Stars (Cherepashchuk et al., 1996).

Name	Spectra	P	e	M_{WR}	$M_{\odot}$
HD 63099	WC5+O7	14.305	0	7	25.0-11.0
γ^2 Vel	WC8+O9I	78.5002	0.4	21	39
HD 90657	WN4+O5	8.255	0	17	36
HD 92740	WN7+O6.5-O8.5	80.34	0.56	86.4	31
HD 94305	WC6+O6-8V	18.82	0	19	40
HD 94546	WN4+O7	4.9	0	9	26
HD 97152	WC7+O7V	7.886	0	11	19
HDE 311884	WN6+O5V	6.34	0	48	57
θ Mus	WC6+O9.5I	18.341	0		
HD 137603	WC8+B0Ia	26.9	0	> 5	> 27
HD 152270	WC7+O5	8.893	0	5	14
HDE 320102	WN4+O7	12.6	0		
CV Ser	WC8+O8-9V-III	29.707	0	14	29
HD 186943	WN4+O9V	9.555	0	16	35
HD 190918	WN5+O9.5I	112.8	0.48	13	29
V444 Cyg	WN5+O6	4.212424	0	9.3	27.9
HD 193793	WC6+O4V	2900	0.84	27	50
CX Cep	WN5+O5V	2.1267	0	7.0-20.0	16-28.3
HD 211853	WN6+O?	6.6884	0	14	26
CQ Cep	WN6-7+O9II-Ib	1.641246	0	40-17	30-20
B 22	WC6+O5-6V-III:	14.926	0.17	12	35
B 31	WC4+O?+O8I:	3.03269	0		
B 32	WC4+O6V-III:	1.91674	0	5	30
SK 188=AB8	WO4+O4V	16.644	0.19	14	52
HD 5980	WN4+O7I	19.266	0.49ph	8	27
AB 6	WN3+O7	6.681	0	8	47
HD 62910	WN6+WC4	85.37:	0.4:		
HD 192641	WC7+abs	5680	0.1:		
HD 193077	WN5+abs+?	1538	0.3		
HD 193928	WN6+?	21.64	0		
AS 422	WN+WC+?	22	0		
B 26	WN7+?	1.9075	0		
B 65	WN7+?	3.0032	0		
B 72	WN6+B1Ia	4.3092	0		
B 82	WN6+O5V	4.377	0		
B 86	WNL/Of	52.7	0		
B 87	WN6+?	2.7596	0		
B 90	WN77+?	25.17	0		

Table 2. Data of SD Close Binary Systems (Karetnikov and Andronov, 1989).

Name	P	M_1	M_2	Name	P	M_1	M_2
V453 Sco	12.004	30	27	U Sge	3.380619	5.7	1.9
V448 Cyg	6.519733	22.4	17.5	RS Vul	4.477661	4.65	1.45
XZ Cep	5.097227	18.1	14.2	RW Gem	2.865497	5.35	1.6
V356 Sgr	8.896099	12.3	4.7	DM Per	2.727742	5.5	1.65
SZ Cam	2.698438	20.4	5.1	TX UMa	3.063317	3.7	1.1
RZ Sct	15.1907	16.3	3.1	U Crb	3.452204	4.8	1.4
U Cep	2.493099	4.2	2.8	λ Tau	3.952948	6.6	1.75
Z Vul	2.454926	5.4	2.25	IZ Per	3.687662	5.2	1.35
FW Mon	3.873583	3.8	1.45	TU Mon	5.049029	8.1	2
u Her	2.051026	7.9	2.85	QS Aql	2.5133	3.85	0.85
RS Sgr	2.415683	6.1	2.2	GG Cas	3.758719	5	1.1
GT Cep	4.908749	8.1	2.75	β Per	2.867324	3.7	0.8
WW Cyg	3.317746	4.85	1.65	UX Mon	5.9045	3.5	1.5
ZZ Cas	1.243527	4.9	1.65	V505 Sgr	1.182875	2.1	1.15

Table 3. Data of Close Binary Systems [14].

Name	Spectra	P	e
AI Phe	F7V+K0IV	24.5923	0.19
RY Per	B5V+F6IV	1515.6	0.22
τ Per	G4III+A4V	6.8636	0.73
γ Per	G8III+A3V	5350	0.72
β Per	B8V	2.86773	0.02
RW Tau	B8V+K0III	2.7688	0.29
VV Mon	K0IV+F6	6.0506	0.03
RY Gem	A0V+K0IV	9.3009	0.16
p Vel	F3IV+F0V	10.2104	0.51
HD133822	G5IV+G5IV	17.8336	0.2
ε Lup	B3IV+B3V	4.5598	0.26
α CrB	B9.5IV+G	17.3599	0.37
W UMi	A3+G9IV	1.7012	0.09
HD153890	F3IV-V+F3V	34.8189	0.42
MM Her	G2V+K2IV	7.9604	0.04
96 Her	B3IV+B3IV	12.4573	0.54
V Sge	B7.5V+G4III-IV	1370	0.19
ψ Cyg	G8III-IV+G8III-IV	434.086	0.52
HD191201	B0III+B0III	8.3343	0.5
θ Aql	B9III+B9III	17.1243	0.61
HD197649	F6IV-V+G8V	18.0668	0.09
Y Cyg	B0IV+B0IV	2.9963	0.14
HD206874	F2IV+F2IV	3.2295	0.02
2 Lac	B6IV+B6V	2.6164	0.04
BW Aqr	F8IV+F7IV	6.7197	0.18
W Cru	F6IV+F6IV	2.9685	0.02
NY Cep	B0IV+B0IV	15.2765	0.49
CW Cep	B0.5IV-V+B0.5IV-V	2.7291	0.03
94 Aqr	G5IV+K2V	2323.6	0.08
HD22005	B3IVn+B3Ivn	4.4151	0.55
Y Psc	A3V+K0IV	3.7659	0.12

time scale with a rate $\sim 10^{-4}\ M_{\odot}$/year (Cherepashchuk, 1981).

3. Cyg X-1: in this short period ($P \cong 4.8$ hours) X-ray binary system, the optical star is WR star, which is formed most probably through spiral-in mass loss mechanism during common envelope stage of evolution of massive close binary system (Cherepashchuk and Moffat, 1994). All these examples give us direct observational evidences for importance of mass transfer through Roche-Lobe overflowing in massive close binary systems.

5. Conclusion

Results of our investigations allow us to conclude that at least 70% of all known WR+O binary systems (with orbital period $P < 20^d$) where formed as a result of mass transfer in massive close binary systems.

Therefore, mass transfer through Roche lobe overflowing in massive close binary systems is an important mechanism of evolution in these interacting binaries.

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Table 2 (continued).

Name	P	M_1	M_2
RY Per	6.863566	5.4	1.1
TV Cas	1.8126	2.75	1.3
AI Dra	1.198814	2.3	1.05
TW Cas	1.428325	2.55	1.15
W UMi	1.701158	2.9	1.25
δ Lib	2.327353	3	1.3
XZ Pup	2.192306	3	1.2
RW Mon	1.906091	2.55	1
V548 Cyg	1.80524	3.05	0.95
IM Aur	1.247335	3.1	0.9
SW Cyg	4.572839	2.35	0.65
RW Tau	2.768844	2.95	0.8
AQ Peg	5.548503	2.2	0.55
Y Psc	3.765876	2.14	0.52
TT Hya	6.953429	2.05	0.55
S Cnc	9.484551	2.33	0.17
QY Aql	7.22959	2.15	0.65
RY Gem	9.300525	2.8	0.59
VV UMa	0.687378	2.1	0.48
KO Aql	2.864022	2.5	0.5
AB Per	7.16025	2.4	0.5
W Del	4.806043	2.3	0.46
UU Oph	4.396766	2.7	0.5
TW Lac	3.037494	2.1	0.4
ST Per	2.648325	2.25	0.4
T LMi	3.019912	2.35	0.33
TY Peg	3.092234	2.3	0.3
S Equ	3.436066	3	0.37
AS Eri	2.664151	1.93	0.21
DN Ori	12.96626	2.65	0.18
X Tri	0.971527	1.75	1
DL Vir	1.315475	1.8	0.95
RZ Dra	0.550877	1.5	0.72
AT Peg	1.146079	1.7	0.8
TW Dra	2.806834	1.7	0.8
U Sct	0.954985	1.9	0.75
SX Hya	2.895697	1.65	0.58
RZ Cas	1.195252	1.75	0.6
Y Leo	1.686081	1.8	0.6
RW Crb	0.726411	1.5	0.4
UX Her	1.548842	2	0.5
Z Dra	1.357439	1.65	0.41
RX Hya	2.28159	1.5	0.38
BD Vir	2.548439	2.1	0.5
RT Per	0.8494	1.3	0.31
SS Lib	1.437997	1.7	0.4
UW Vir	1.81073	1.75	0.4
RY Aqr	1.966594	1.3	0.3
TW And	4.122773	1.7	0.37
Y Cam	3.305507	1.9	0.4
XX Cep	2.337301	1.7	0.27
XZ Sgr	3.275555	1.8	0.25
R CMa	1.135939	1.5	0.18
S Vel	5.933666	1.6	0.19