ON THE OBSERVED PHYSICAL PROPERTIES AND EVOLUTIONARY TRENDS OF HOT SUBDWARFS IN BINARY SYSTEMS

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ABSTRACT. In our brief review we summarize the latest advances in studies of white dwarfs both as single objects and the components of binary systems. We discuss the observed properties of the hot subdwarfs(sdws), the various techniques of their discovery and some peculiarities of their evolution following the final stages of AGB, both for single stars and binary cores of PN. We find that the observed statistics of sdws clearly point to drastically different evolutionary histories for sdws belonging to very wide pairs and those found in close binaries.

Key words: stars: binary: AGB; stars: evolution-stars:mass loss;stars: rotation-white dwarfs.

1. Introduction

In the last twenty years we witness an ever increasing interest among astronomers in studying physical properties and final stages of evolution of medium mass stars leading to formation of wide dwarfs (WD). Roughly during one generation observational and theoretical research of WD transformed into one of the most flourishing branches of modern astrophysics, a cosmic laboratory for a detailed verification of the predictions of WD theory, more specifically mass-radius relation derived by S.Chandrasekhar almost seventy years ago (for the most recent successes in this field see articles by Wood (1995), Shipman *et al*(1997),Shipman and Provencal (1999), Provencal *et al*(2001). There are several important reasons behind these spectacular achievements and the most impressive of them deserve at least a brief enumeration.

1) Although even today the bulk of all known to us WD lie within 25 pc from us, the number of the newly discovered WD is rapidly growing and the latest McCook & Sion *Villanova Catalogue of Spectroscopically Identified White Dwarfs* (see McCook & Sion (1999) contains entries for 2249 WD stars (for more details on catalogues, data bases and Websites of WD see the paper by Holberg *et al*(2001).

2) It is universally acknowledged that WD-s are the end product of evolution of stars with initial masses between $0.5m_\odot$ and $8m_\odot$ which implies that 98% of all stars are or will be WD-s (if one applies the standard "Salpeter mass function" to estimate the fraction of total stellar mass contained in existing and "would be" WD-s).

3) Since the seminal paper by I.Shklovski who first noticed the rough coincidence between the velocity of expansion of planetary nebulae (PN) and the terminal wind velocities for red giants and conceived its deep evolutionary implication, a remarkable progress has been achieved in both observational and theoretical investigations of the internal structure and evolution of AGB stars leading to superwind, ejection of the extended convective envelope which finally becomes visible as PN illuminated by the bare core - emerging hot subdwarf (sdw) star, the progenitor of future WD. This in its turn inspired both observers and theoreticians to study even more closely the questions of morphology and kinematics of PN, to look for the role of duplicity of illuminating stellar source in shaping PN-s, to explore the physical mechanisms governing the formation of novae and more generally cataclysmic binaries from initially wide pairs.

4) Because the theoretical treatment of the cooling of WD stars is relatively simple (at least for the early stages before effects of crystallization in the interiors of WD become important) it soon became clear that WD can serve as a powerful tool for measuring the age of Galactic disc population provided that one possesses a statistically sufficient observed population of WD-s of different ages. This is due to the fact that the cooling time of WD is inversely proportional to its intrinsic luminosity, therefore we should see more and more WD-s as we proceed to the fainter objects until the luminosity function turns down because of the finite age of the Galaxy. In addition the location of the turning point of the evolutionary tracks on the $H-R$ diagram at the onset of the cooling process of the new borne hot sdws

appears to be very similar for PN-s discovered in other galaxies thereby making the so-called PN luminosity function a useful tool for measuring distances to the extragalactic PN-s (for a detailed discussion of these and related problems see, for instance, the articles by Jacoby (1989)), Iben, Laughlin (1989), Wood (1992)).

5) In addition to the galactic and extragalactic outreach of WD research discovery of rapid oscillations in WD like PG 1159 stars opened up the new horizons for probing both the deep interiors and the thin "crust" of the evolved WD. This new branch has culminated in project WET enabling to achieve an unprecedented accuracy in measuring the masses of individual WD through a detailed study of their oscillation spectra (for a more recent progress in astroseismology of WD see, for instance, detailed discussion of the current state of WET in the article by Kleinman (1999) and references therein, also a number of articles "Variable White Dwarfs" in the Proceedings of the 12th European Conference on White Dwarf Stars (2001), see the list of references to this article).

Until recently the observed statistics of binaries with the hot sdw primaries has been significantly biased since a number of observational selection criteria favors discovery of strongly interacting binaries with short orbital periods. In a striking contrast to this trend peculiarities of the wide pairs up to most recent times remained largely non-explored (with an exception of a limited number of symbiotic stars).

The so-called precataclysmic binaries (PCB) provide an important link between the short period cataclysmic variables and wide pairs.PCB-s is a small group of detached close binary systems, which are observed at centre of planetary nebula, consisting of a hot white dwarf or a subdwarf accompanied by an essentially unevolved low mass cool companion $m_2 \leq 1m_\odot$. PCB orbital periods are so short (typically less then two days) that they can only have been formed via a common envelope evolution (see, for instance, Bond et al 1991, Ritter 1986). Despite the fact that PCB-s have been intensively studied for the last twenty years a number of important problems remains open. PCB-s are discovered mostly due to a pronounced irradiation effect (conveniently called "reflection effect"). Since the early paper by Paczynski and Deaborn (1980) the problem of anomalously high reflection effect amplitude remains unsolved (see a discussion in paper by Hildtich (1994)). It seems that the key to the solution of this problem lies in the reprocessing of Lyman continuum of hot sdws in the uppermost atmospheric layers of the late type unevolved companion (for more details see the paper by Pustynki, Pustylnik and Kubat (2001)).

2. Statistics of the Hot Subdwarfs in Binaries

To understand better the difference between the single sdws and their counterparts in binary systems several groups of investigators have undertaken systematic searches for the late-type companions of sdws.Thus, Saffer, Green and Bowers (2001) have studied a sample of 70 bright B type sudwarfs (SdB) and obtained accurate radial velocities for them. According to these authors SdB stars fall into three distinct groups based on their kinematic and spectroscopic properties. No detectable spectral lines from a cool companion have been found in Group I and only insignificant velocity variations have been detected. These objects constitute around 35% of all SdB stars in Saffer's *et al* sample and this estimate sets an upper limit for the total fraction of non-binary SdB-s. Group II SdB-s are single-lined spectroscopic binaries, comprising about 45% of the objects from the same sample. The remaining 20% of SdB-s are binaries which indicate the presence of additional spectral lines from a cool MS or a subgiant companion. In this Group III all systems reveal slowly varying or nearly constant radial velocities indicating orbital periods ranging from many months to several years. According to Saffer et all "the current data are insufficient to rule out the possibility that some SdB-s in Group I may be analogs of the wide binaries in Group III with undetectable faint companions. The clear division into three groups with such disparate properties suggests very different evolutionary histories even though the current physical status are essentially indistinguishable". These results may be confronted with those of Maxted, Marsh and North (2001) who found 23 stars in a sample consisting of 44 SdB stars definitely to be short period binaries. This conclusion corroborates an earlier estimate of 54% – 66% obtained by Allard *et al*(1997) based on circumstantial evidence from $UBVRI$ colours of sdws (in fact Bergeron *et al* (1995) have demonstrated that model atmosphere calculations reproduce quite successfully observed $M_v - (V - I)$ diagram for DA and non-DA white dwarfs).

Several observational tests can be proposed to discriminate between different evolutionary scenarios leading to formation of WD-s. In particular statistically more rapid axial rotation is expected for hot sdws in binaries (when compared to single objects). In reality Koester *et al* (1999) have determined $vsini$ for 26 WD by fitting H_α rotationally broadened profiles to the observed ones. Only in 3 cases $vsini$ definitely exceeded $50km/s$ (in all these cases magnetic field higher than 40 KG was detected), only in one case the presence of a companion was established beyond any doubt (similar results have been obtained earlier by Heber *et al* (1997)). These results are in accord with the theoretical predictions of Spruit (1998) who presented numerous arguments favouring the idea that the rotation of WD is not a remnant of the angular momentum of their MS progenitors but a result of the mass loss process during the AGB stage. According to this author strictly axisymmetric mass loss during the AGB stage from uniformly rotating stars would lead to WD with rotation periods $P > 10y$ but small random non-axisymmetry of order 10^{-3} in the mass loss process add sufficient angular momentum to produce observed rotation of order 1 day. Unfortunately up to now the existing data on radial velocities of sdws in binaries remains scarce and scattered. On the other hand, two ultra-rapid K-dwarfs $2REJ004+093$ and $2REJ0357+287$ (projected velocities respectively $90km/s$ and $140km/s$) have been discovered in wide binaries with hot sdws (see Jeffries and Stevens (1996)). Jeffries and Stevens propose a model which explains the origin of such systems as the consequence of the spinning up late type components due to accretion of the slow wind from the AGB progenitor.

Different evolutionary histories for very wide pairs and relatively close binaries with hot sdws may solve a certain controversy concerning the role of binarity in the observed diversified morphology of PN-s. According to Tutukov, Yungelson and Livio (1993) the fraction of all PN-s posessing binary cores is $\sim 22\%$ whereas Schwarz and Corradi (1995) find 11% among the bipolar PN-s. Bond and Livio (1990) who studied 10 precataclysmic binaries MT Ser, UU Sge, V477 Lyr, V664 Cas, VW Pyx, V 651 Mon, Abell-35, LSS 2018, LoTr1, LoTr5 and their environments derive the following conclusions: 1) in nebulae with binary central cores no double shells have been detected typical for PN-s, 2) roughly in 50% of PN-s elliptical or bipolar structures have been observed, 3) morphology of at least three PN-s unambigously points to the interaction effects with interstellar medium. The fraction of PN-s with such features is higher for binary cores in comparison with single objects.

Bearing in mind resluts of Saffer *et al* (2001) it is clear that actual fraction of PN-s with binary cores may be significantly underestimated for wide pairs. Although the original interacting winds model of Kwok, Purton and Fitzgerald (1978), later generalized by Kahn and West (1985) and by Balick (1987) does not invoke specifically the effects of binarity to explain elliptical and bipolar shape of PN, it is evident that even in very wide systems the presence of a companion should influence both the overall distribution of circumstellar material and its chemical composition due to effects of accretion of ejecta (see also a discussion of various scenarios for production of elliptical and bipolar shapes of PN-s in Hrivnak (2001)).

There are several independent methods of discovery of the faint late type components accompanying hot sdws. One of the most promising technique lies in the detection of infrared flux excesses in the spectra of hot sdws through application of JHK photometry of sdws in combination with the *IUE* data for spectral distribution of sdws. Although this technique has its limitations (it implies a reliable knowledge of the gravity acceleration for sdw which suffers from the uncertainties in the radii values, also it is a common practice to assume the average values of $m_{\rm sdw} = 0.55m_\odot$) it enabled to discover 88 new binaries with sdws as the primaries (for details see the papers by Thejll *et al*(1995) and Ulla, Thejll (1998)). A circumstellar origin of IR excess has been excluded by Thejll *et al*(1995). Essentially the same method has been applied the other way round: by inspecting the spectral energy distribution of late type MS stars in far UV it is possible to detect the signatures of the hot companions shortward of $1600\AA$. Nine such systems have been identified through *ROSAT,EUVE* and *IUE* observations summarized by Barstow *et al* (1994). Unfortunately, these indirect methods cannot provide data on orbital parameters without follow-up spectroscopic and photometric observations. At least for some of these objects inspection of *HIPPARCOS* data should give the distances to these binaries, while in absence of eclipses and pronounced irradiation effects one can get at least the lower limits to separation between the components and the order of magnitude estimate of anticipated orbital period.

3. Different Evolutionary Histories for Moderately Wide Binaries and Wide Pairs ?

In Table I reproduced from paper by Burleigh *et al* (2001) the estimated separations and orbital periods of some binary systems resolved by HST with the hot subdwarfs primaries and the late type MS stars or subgiants as the secondaries are given. We use this small sample for making rough estimates of the plausible orbital parameters of the progenitors of these systems.

To see more distinctly the differences between the consequences of disparate evolutionary histories for WD in close and wide binaries we compare the cooling time $t_{\rm cool}$ of WD and the time scale for the mass loss during the final stages of AGB immediately preceding the emergence of the hot sdw from the ejected envelope of AGB star.

$$t_{\rm cool} \approx 9.41 \cdot 10^6 yr (\frac{A}{12})^{-1} \mu^{-2/7} (\frac{\mu_e}{2})^{4/3} (\frac{m}{m_\odot})^{5/7} (\frac{L_\odot}{L})^{5/7}$$

Here μ is the mean molecular weight of the giant's envelope, μ_e is the mean molecular weight per electron in the core, A -is the atomic weight of the matter in the core. Assuming that the masses and luminosities of the WD in wide pairs like HD27483 or 14 Aur C are comparable to those typical for such PCB-s like UU Sge or V477 Lyr (see Polacco and Bell (1993),(1994)) we estimate $t_{\rm cool}$ as $7.7 \cdot 10^5 yr$ and $10^4 yr$ for masses of WD respectively $0.51m_\odot$ and $0.63m_\odot$ and luminosities of the hot sdws taken from papers of Polacco and Bell. Confronting these values $t_{\rm cool}$ with the time scales of increase the temperature of the hot sdw due to the

Table 1: Estimated physical parameters for the resolved binaries

System	Sp.type	Dist(pc)	$P(yr)$	$a(R_\odot)$
HD2133	F7V+DA	140	590	$1.7 \cdot 10^4$
HD27483	F6V+DA	46	260	10^4
14 Aur C	F4V+DA	82	1307	$2.9 \cdot 10^4$
RE J1925-566	G7V+DA	110	95	5100
HD223816	F8V+DA	92	290	$1.1 \cdot 10^4$
56 Per	F4V+DA	42	47	3190
MS 0354.6-3650	G2V+DA	400	6200	$8.3 \cdot 10^4$
ζCyg	G8IIIp+DA	46	18	1680

decrease of the mass of hydrogen envelope $\tau_{\rm nuc}$

$$\tau_{\rm nuc} \approx 6 \cdot 10^4 yr(\frac{L}{1000L_\odot})^{-1}(\frac{m_{\rm env}}{10^{-3}m\odot})$$

and time scale $\tau_{\dot m}$ of the mass loss during the phase of superwind

$$\tau_{\dot m} \approx 3 \cdot 10^4 yr(\frac{\dot m}{10^{-8}m_\odot/yr})^{-1}(\frac{m_{\rm env}}{10^{-3}m\odot})$$

we see that $t_{\rm cool}, \tau_{\rm nuc}, \tau_{\dot m}$ are all roughly of the same order magnitude and less or comparable to $\tau_{\rm therm}$ for the cool companion of the hot sdw. This means that during the phase of superwind and after emergence of the hot sdw following "shedding" of the envelope the distant companion in a binary had no time enough for accreting appreciable portion of the material lost from sdw. We use this fact to estimate the initial separation between components of the binaries shown in Table I.

For very wide pairs with the estimated orbital periods $10^2 - 10^3$ yr the size of the orbit found from the Kepler's third law $a = 214R_\odot\, m_1^{1/3}(1+q)^{1/3}\, P_{yr}^{2/3}$ is indicated in the last column of the Table I (assuming $m_1 = 1m_\odot$ and $q = 0.5$). For half of the systems in the Table I the size of orbit is $a \geq 10^4\, R_\odot$. This means that such wide pairs most probably escaped in past the phase of common envelope because even during the AGB stage the progenitor of WD had no chance to fill in its Roche lobe or because due to the very large size of the orbit the magnetic braking and the ensuing orbital decay could not operate efficiently. Arguing in that way we ignore the evolution of the orbit in the past. If, on the other hand, we make an assumption of the net mass loss from the AGB star without a considerable accompanying angular momentum loss, then using the relation $PM^2 = const$ (M being the total mass of a binary) for $M \simeq 5m_\odot, q = 0.5$ and $m_{\rm wd} = 0.6m_\odot$ we find that initial separation between the components was of order $10^3 R\odot$. Thus, the validity of conventional concept about the Roche lobe overflow and subsequent formation of common envelope in application to such binaries looks problematic.

A reasonable estimate of an impact caused by a distant companion upon the properties of stellar wind from AGB can be found using the recently published results of Frankowski and Tylenda's investigation(2001) of stellar wind peculiarities in a binary.

Frankowski and Tylenda (2001) have explored the influence of a companion on the wind from the giant in the AGB stage in a binary system. They have derived a simple relation for the equatorial-to-polar wind intensity contrast

$$\frac{\dot m_{\rm eq}}{\dot m_{\rm pol}} = 1 + \frac{(a - 4ab - 4c)}{4\gamma}(2+5q)\xi(q)^3(\frac{R}{R_L})^3$$

Here q - is the mass ratio , R -the radius of a giant, $\xi = R_L/A$, A being a semi-major axis of the relative orbit, R_L - the radius of the Roche lobe. γ is a free parameter describing the effectiveness of the Newtonian gravitational force (it accounts for the effects of pulsation, radiative pressure and convective motions all acting to diminish the gravity on the giant's surface), α is a parameter describing the effect of gravity darkening ($\alpha = 0$ for uniform temperature distribution and $\alpha = 0.25$ for the atmosphere being in a state of strict radiative equilibrium according to von Zeipel's theorem), parameters a, b, c are determined from the power law approximation of the mass loss rate $\dot m \sim R^a\, T_{\rm eff}^b\, g^c$ and found from the model of stellar wind for AGB stars (for example, in case of the models by Arndt *et al* (1997), $a = -4.70, b = -2.14, c = -2.88$). For reasonable combinations of parameters a, b, c, γ, α Frankowski and Tylenda find the effect of the contrast ($\dot m_{\rm eq}/\dot m_{\rm pol} - 1$) ranging between $10^{-4} - 10^{-3}$ for ($R/R_L \ll 1$) up to 1-5 for $R/R_L \sim 1$. Using the above-given expression for $\frac{\dot m_{\rm eq}}{\dot m_{\rm pol}}$ we can easily verify that effect of the wind contrast between equator and pole will not influence appreciably the above-given estimate of the initial separation between the components. Thus, the following conclusion seems to be unavoidable: evolutionary history for very wide pairs (with $P_{\rm orb} \geq 100yr$) should be drastically different from binaries with initial orbital periods $P_{\rm orb} \ll 100yr$. In view of the above-stated a comparative study of the evolutionary history for binaries with moderate masses ($M \leq 10m_\odot$) and orbital periods ($P_{\rm orb} \sim 10 - 100yr$) deserves a special investigation.

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