Astronomical and Astrophysical Transactions (*AApTr*), 2014, Vol. 28, Issue 3, pp. 249–258,
ISSN 1055-6796, Photocopying permitted by license only, ©Cambridge Scientific Publishers

Late stages of the evolution of Close Compact Binaries

A.V. Tutukov, A.V. Fedorova*

Institute of Astronomy, Russian Academy of Sciences, 48 Pyatnitskaya Street, Moscow, 119017, Russia

Received 13 March, 2013

The paper presents scenarios of the evolution of close binaries resulting in the most intensive explosive phenomena in the stellar Universe – Type Ia supernovae and gamma-ray bursts. For Type Ia supernovae we derive the conditions for the accumulation of the limiting mass by the degenerate dwarf in the close binary. Accretion onto the degenerate dwarf can be accompanied by supersoft X-ray radiation with luminosity $\sim 10^4\,L_\odot$. Gamma-ray bursts are believed to accompany the formation and rapid evolution of compact accretion-decretion disks during the formation of relativistic objects – black holes and neutron stars in the course of evolution of close binaries. Numerical models of the evolution of some close binaries that result in Type Ia supernovae explosions and gamma-ray bursts in our Galaxy are presented.

Keywords: Stars: binary systems – Stars: supernovae

1 Introduction

The idea about the thermal instability of thermonuclear reactions in stellar degenerate matter, leading to detonation of nuclear fuel, is now the basis of all modern models of Type Ia supernovae (SNIa) (Gurevich and Lebedinskij, 1946). Hoyle and Fowler (1960) have demonstrated that the growth of the mass of carbon–oxygen (CO) degenerate dwarf to Chandrasekhar mass $\sim 1.4\,M_\odot$ leads to its contraction and heating, and finally to a thermonuclear explosion of a supernova scale. The energy produced by the burning of CO matter and by the radioactive chain: ^{56}Ni–^{56}Co–^{56}Fe. The "commonality" of light curves and energy releases of SNIa is a consequence of the universality of Chandrasekhar mass and similarity of dwarf chemistry before the explosion. The absence of observed lines of hydrogen and helium in SNIa's spectra excludes red supergiants with CO cores from possible progenitors of these supernovae. Therefore all scenarios for these supernovae, proposed during the last several decades, are based on the growth of CO dwarf masses in the course of accreting the matter of different-nature close satellites to form an appropriate close binary system (CBS) (Iben and Tutukov, 1985) (Fig. 1). The initial primary of the CBS is a progenitor of

*Email: afed@inasan.ru

a sufficiently massive degenerate CO dwarf and the secondary is a source of matter for the growth of dwarf mass to a critical mass.

It is necessary to note here that the most massive degenerate dwarfs arising in the evolution of stars with initial masses $\sim 10\,M_\odot$ appear to be oxygen–neon (ONe) ones because of the "soft" burning-out of carbon in their cores. Oxygen and neon burning in the course of the thermonuclear burst of these dwarfs does not lead to SNIa explosion because of low nuclear fuel energy. As the result, a ONe dwarf of a Chandrasekhar mass $\sim 1.4\,M_\odot$ probably collapses to form a neutron star (NS) (Iben and Tutukov, 1985) of a very low mass $\sim 1.25\,M_\odot$ (Kitaura et al. 2006), because of the relativistic defect of the mass. As the result we arrive to a conclusion that probably only explosions of degenerate CO dwarfs in close binaries lead to SNIa, producing the main part of iron in Universe.

The estimated SNIa rate in our Galaxy is ~ 0.003 per year (Scannapieco and Bildstein 2005), as it follows from observations. The star formation rate in our Galaxy is $\sim 1\,M_\odot$/yr. In other words, one SNIa per $\sim 300\,M_\odot$ newly formed stars. The SNIa rate is approximately a factor of ten lower than the observed combined rate for massive supernovae (SNII and SNIb,c) (Scannapieco and Bildstein 2005). It is of great interest and importance that the SNIa rate seems to be related not only to the mass of the parent Galaxy, but also to the history of star formation in the Universe (Sullivan et al. 2006). The SNIa rate reaches its maximum at $z \sim 1$ and decreases at larger redshifts ($z > 1.5$) (Dahlen et al. 2004), which indicates that the average lifetime of their progenitors is $\sim 3 \times 10^9$ years. Note that some SNIa have ages less than 10^9 years (Barris and Tonry 2006). To estimate the minimum lifetime of SNIa progenitors, it was important that their rate is nearly a factor of four higher in E galaxies with active star formation than in ordinary "inert" E galaxies (Della Valle et al. 2005). The duration of the star-formation burst in a galaxy is of the order of its dynamical timescale, $\sim 10^8$ years. This implies that even this short time is sufficient for at least some of the supernova progenitors to "ripen". In addition, it suggests that some SNIa have ages comparable to the Hubble age (10^{10} years), since they are also observed in ordinary E galaxies. It is obvious that the dispersion of age for SNIa progenitors is large, and it is likely that several scenarios for their formation occur.

2 SCENARIOS FOR SNIa EXPLOSIONS

We will briefly describe the basic scenarios now considered to be the most probable ways to produce SNIa, in the order specified in Fig. 1.

2.1 Symbiotic binary stars (SS)

Historically, the first model that assumed the binarity of the progenitor was the symbiotic binary model (Tutukov and Yungelson 1976). Observed systems of this type consist of a red (super)giant (possibly a RCrB star in some cases) with an intense stellar wind that is close to filling its Roche lobe, and a degenerate dwarf that accretes part of the giant's stellar wind matter. The fraction of the stellar wind accreted is estimated from the relation $(mR/Ma)^2$, where m and M are the masses of the accretor and donor and R and a are the radius of the donor and the semimajor

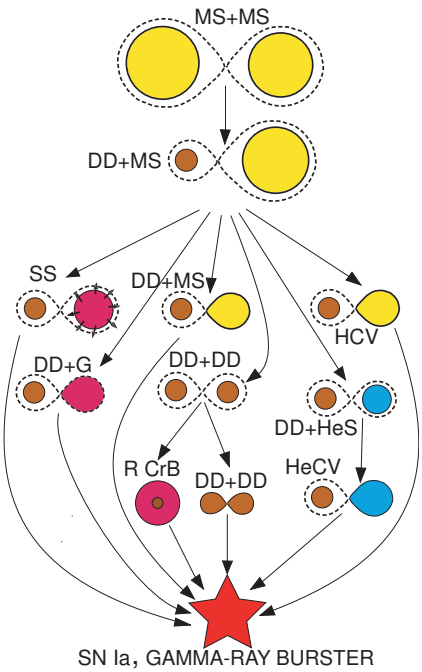


Figure 1 Evolution of close binary systems leading to SNIa explosions. MS denotes a main-sequence star, DD a degenerate dwarf, G a giant, SS a symbiotic star, HeS a helium star, HCV a cataclysmic variable with a main-sequence donor, HeCV a cataclysmic variable with a helium donor, and R CrB R Corona Borealis star.

axis of the orbit. This estimate assumes that the wind velocity is of the order of the escape velocity from the donor surface. It is clear that, when the components have similar masses and the donor is close to filling its Roche lobe, the degenerate dwarf in a symbiotic binary can accrete about 10% of the donor envelope. The recurrent outbursts of shell hydrogen burning observed in such systems support the possibility that an accreting massive degenerate dwarf gradually accumulates the critical mass and can explode as a SNIa. The existing limit on the observed loss rates for hydrogen rich matter by pre-SNIa ($\sim 10^{-5}\,M_\odot$/yr) does not rule out this scenario even for this case (Lundqvist et al. 2006), which provides to the known examples of SNIa with signs of hydrogen in their envelopes (Deng et al. 2004) and stellar winds with intensities $\sim 3 \times 10^{-6}\,M_\odot$/yr in their vicinities (Immler et al. 2006).

2.2 Close binaries with a low-mass giant donor (DD + G)

Another way to provide the necessary mass-exchange rate between the components is realized by semi-detached systems of low mass (0.8–1.2 $M_\odot$), giant donors with degenerate helium cores (Wheelan and Iben 1973). The mass of the helium core should be 0.4–0.5 $M_\odot$. The radii of giants with such masses are 300–600 $R_\odot$, while the semimajor axes of close binaries are around a thousand solar radii. Thus, the

formation of a massive degenerate CO dwarf requires that the progenitor star expand to $R > 1000\,R_\odot$. The low-mass companion will be absorbed by the common envelope, and the semimajor axis of its orbit will be reduced below $\sim 100\,R_\odot$. Consequently, the direct formation of close binaries suitable for this scenario seems now impossible. However, binary radio pulsars in globular clusters possess degenerate helium components in close systems with semimajor axes (100–600) $R_\odot$ (Camilo and Rasio 2005). Such systems in dense star clusters are probably formed through exchange capture in the course of collisions between binaries and single NSs. In the same way, in globular clusters, fairly wide systems of massive CO dwarfs and main-sequence (MS) stars with masses close to the solar mass can also be formed. However, since only a small fraction (~ 0.001) of stars in the Galaxy are in globular clusters, this scenario has a small rate of realization, which is basically specified by the rate of exchange captures, depending on parameters of globular clusters.

2.3 Close binaries with a main-sequence donor (DD+MS)

It has long been known that, if the component-mass ratio exceeds ~ 1.2 and the donor has a radiative envelope that fills its Roche lobe, mass exchange occurs on the thermal timescale of the donor (Masevich and Tutukov 1988), which can be a main-sequence star of appropriate mass (Fig. 1). It has been estimated that, to provide the necessary mass-exchange rate, the donor mass should be about 2 $M_\odot$. The conditions for quasi-steady-state burning of hydrogen in shell sources in a spherically symmetrical dwarf of solar chemical composition (Masevich and Tutukov 1988):

$$dM_{\rm CO}/dt = (0.3{-}1) \times 10^{-6}\,(M_{\rm CO}/M_\odot - 0.5)\;\; M_\odot/{\rm yr} \qquad (1)$$

We estimate the possible rates of different mechanisms for SNIa in our Galaxy using a function that describes the initial distribution of close-binary basic parameters previously found by us (Iben and Tutukov 1984):

$$d^3N = 0.2\; d\log(a/R_\odot)(M_1/M_\odot)^{-2.5}(dM_1/M_\odot)\; dq\;\; {\rm yr}^{-1} \qquad (2)$$

This formula gives the rate of such SNIa in our Galaxy only $\sim 10^{-5}$ per year. It is clear that this scenario may provide only a small part of SNIa explosions. The age of such SNIa is $\sim 10^9$ years.

2.4 Close binaries with a degenerate dwarf donor (DD+DD)

The merger of binary degenerate CO dwarfs (Fig. 1) with a total mass above the Chandrasekhar limit is currently considered to be the most promising scenario (Iben and Tutukov 1984). A theoretical estimate for the rate of such events is ~ 0.003 per year (Tutukov and Yungelson 2002), which is close to the observed rate of SNIa. Such binaries are products of evolution of CBS of moderate mass (Iben and Tutukov 1984).

Observations confirm the existence of such binary degenerate dwarfs (Nelemans et al. 2005). Mergers of helium degenerate dwarfs with CO dwarfs yield stars with extended helium RCrB-type envelopes (Iben and Tutukov 1984) at a rate of ~ 0.01 per year (Tutukov and Yungelson 2002). The high mass-loss rate of these stars, comparable to or even exceeding the rate of helium burning at the bottom of the extended

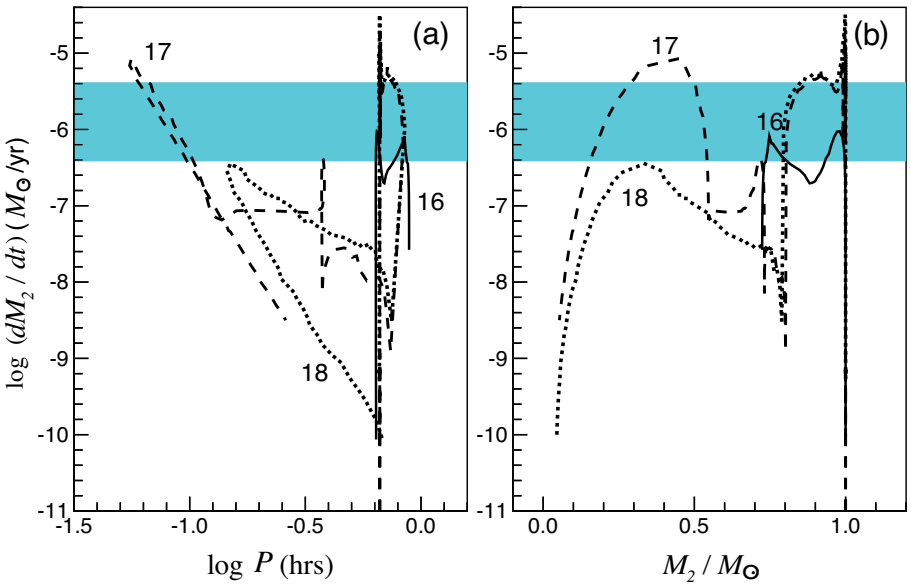


Figure 2 Theoretical evolutionary tracks of close binary systems with a degenerate dwarf donor. (a) Logarithm of the orbital period vs. logarithm of the donor mass-loss rate. (b) Mass of the donor vs. logarithm of the donor mass-loss rate. The figures indicate track numbers in the table [from Tutukov and Fedorova 2007]. The wide gray band indicates the interval of mass exchange rate within which the steady-state burning of accreted matter on the surface of the white dwarf is possible. Different tracks are indicated by different types of lines.

helium envelope, makes explosions of their CO cores unlikely, although they remain still possible for sufficiently massive CO dwarfs. This scenario requires additional numerical studies, as it assumes the existence of supernovae without hydrogen but with helium in the extended envelope of an R CrB star.

We illustrate this scenario by the results of our computations for the evolution of a close binary system whose donor is an evolved helium star at the stage of helium depletion in the core. The initial mass of the helium star is 1 $M_{\odot}$, and the mass of the accretor 1.3 $M_{\odot}$. The computations indicate (Fig. 2) that the mass-loss rate by the donor can reach the steady-state value, both in the initial phases of evolution (track 17) and at later stages (track 18), depending on the initial helium abundance in the donor core. However, for track 16, which corresponds to a more evolved helium donor, the mass-loss rate for the dwarf decreases substantially. Note that the steady-state burning of helium in the envelope of the accreting dwarf provides the condition for the central ignition of carbon in the dwarf (Martin and Tout 2006).

2.5 Close binaries with a non-degenerate helium donor (DD+HeS)

In the case of an accreting degenerate dwarf, a donor can also be a non-degenerate low-mass helium star that fills its Roche lobe (Tutukov and Fedorova 1989). Figure

3 presents the results of our numerical simulations of the evolution of such a system. In this case, the allowed mass of the helium star is 1.4–1.7 $M_\odot$. At the initial stage of mass exchange in such systems, the donor mass-loss rate falls in the region of steady-state helium burning at the surface of the accretor. The mass exchange occurs on the thermal timescale of the donor. However, this is valid within a very narrow interval of initial masses for the helium star ($\sim 0.3\,M_\odot$), and the mass lost by the donor at this stage is relatively small (less than $\sim$ 0.1–0.3 $M_\odot$). Such close binaries are indeed observed (Oliveira et al. 2003). Due to the need to "fine tune" the close-binary parameters, the rate for this scenario with a 1.4–1.7 $M_\odot$ helium donor is low: $\sim 10^{-4}$ per year for our Galaxy, which is insufficient to provide the observed SNIa rate. Note, however, that, in this scenario, the CO dwarf does not have to acquire the Chandrasekhar mass at an exchange rate specified by (2). At lower exchange rates, the envelope of the CO dwarf can accumulate $\sim$ 0.1–0.3 $M_\odot$ of helium (Iben and Tutukov 1991) (tracks 19–22). In such an envelope, helium burning can result in detonation of the binary and an SNIa explosion. The rate of such events likewise does not exceed $\sim 10^{-4}$ per year.

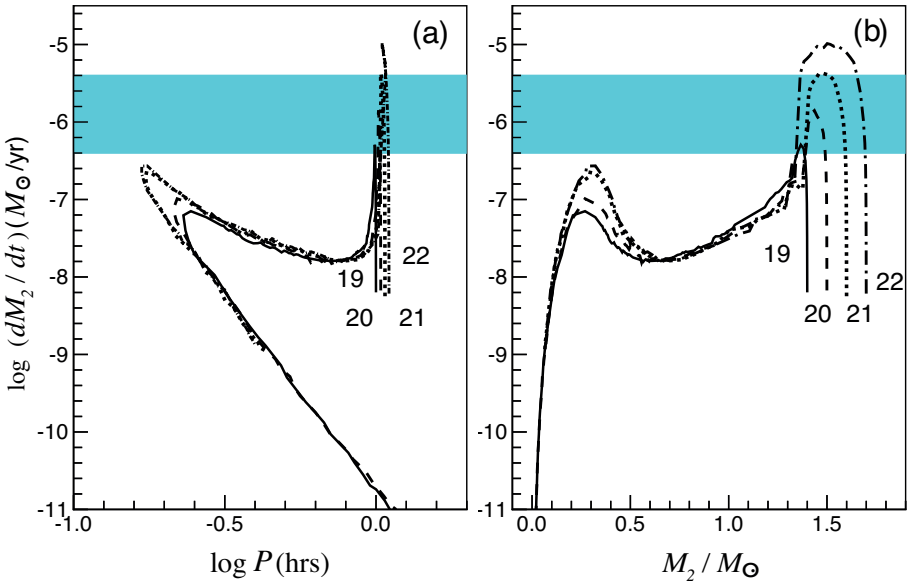


Figure 3 Same as Fig. 2 for a non-degenerate helium donor.

2.6 Cataclysmic binaries (HCV)

For a long time, cataclysmic binaries presented the most attractive and universal model for SNIa (Fig. 1). In these systems, the donor is a low-mass main-sequence star that fills its Roche lobe (Iben and Tutukov 1985). The evolution of such systems can provide the necessary high mass exchange rate, and is probably driven by the

magnetic stellar wind (Masevich and Tutukov 1988). This wind is efficient for the initial semimajor axes in pre-cataclysmic systems (2.5–8) $R_\odot$ (Masevich and Tutukov 1988). The high exchange rate is needed to provide quasi-steady-state hydrogen and helium burning. In this case, intense shell outbursts are excluded, and the degenerate CO (ONe) dwarf becomes a supersoft X-ray source with a luminosity of $\sim 10^4 L_\odot$.

The parameters of such CO (ONe) dwarfs are close to those of sources of supersoft X-ray radiation, such as CAL 83 and CAL 87 (Lanz et al. 2004). CAL 83 has $T_e \sim 5.5 \times 10^5$ K and $M_{\rm CO} \sim 1.3\,M_\odot$, and was identified with a close binary of a period of about one day (Lanz et al. 2004). Other supersoft X-ray sources have orbital periods from 2 h to 600 days (Kahabka and van den Heuvel 2006), confirming the large variety of systems that can provide quasi-steady-state burning of hydrogen, and possibly helium, in the envelopes of CO (ONe) dwarfs. Some are not able to acquire the critical mass, others are accreting BHs, and yet others are massive cores of planetary nebulae. In addition, some supersoft X-ray sources are concentrated in the spiral arms of the Galaxy (Di Stefano and Kong 2003), which suggests they are young and relatively massive. Some supersoft X-ray sources are novae, some are supernovae remnants, and others are unidentified (Orio 2006).

Simulations of the evolution of such systems indicate that the necessary accretion rate can be reached for initial donor masses of 1–1.5 $M_\odot$ and initial accretor masses of $\sim 1\ M_\odot$ (Masevich and Tutukov 1988). The observations show a substantial number of cataclysmic systems with total component masses exceeding 1.4 $M_\odot$, such as EY Cyg and CI Aql (Bianchini et al. 2006). The initial component-mass ratio on the main sequence will be ~ 0.1. In this scenario, formula (2) then yields an estimated SNIa rate of $\sim 10^{-4}$ per year. This value is appreciably lower than the required "observed" value of ~ 0.003 per year; it is therefore likely that this scenario can provide only some fraction of SNIa.

3 Close-binary evolution producing gamma-ray bursts

We briefly consider here the generation of gamma-ray bursts (GRBs) at the late stages of CBS evolution (Fig. 4). Collapse of rapidly rotating cores of Type Ib,c supernovae, collapse of accreting ONe dwarfs into NS and mergers of two NS (or an NS and a black hole) lead to the formation of a compact accretion-decretion disk. Rapid ($\sim 1\ M_\odot$/s) accretion of disk matter on the central compact star results in the energy release $\sim 0.1\ M_\odot^2$ or $\sim\ 10^{53}$ erg in 0.1–1000 s in the form of gamma rays and neutrino. It is the most possible mechanism of generation of GRBs. The GRB rate in our Galaxy is estimated as $\sim 4 \times 10^{-4}$ per year (Cincarini et al. 2006). Taking into account the collimation of the GRB radiation into a cone with an opening angle of only a few degrees yields $\sim 10^{-6}$–10^{-7} per year for this rate, close to the observed value (Matsubayashi et al. 2005).

GRBs are divided into long and short bursts, depending on their duration. These groups are separated by a duration of ~ 2 s. Long GRBs seemed to be related to Type Ib,c supernovae, which are produced by explosions of helium stars in close binary systems, resulting in the formation of quickly rotating neutron stars and black holes (BHs) (Tutukov and Chugaj 1992). Figure 4 presents three scenarios for the generation of long GRBs, related to the core collapse of Wolf–Rayet stars in close binary

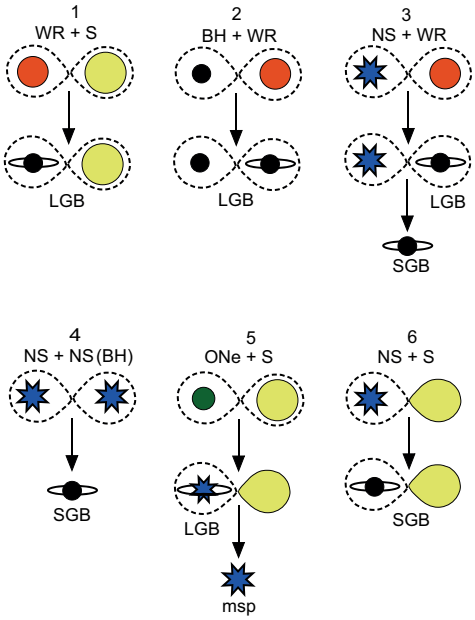


Figure 4 Evolution of close binary systems resulting in GRBs. WR denotes a Wolf–Rayet star; S, an ordinary (non-compact) star; BH, a black hole; NS, a neutron star; LGRB, a long GRB; SGRB, a short GRB; ONe, an oxygen-neon dwarf; and msp, a millisecond pulsar.

systems into Kerr BHs (Tutukov and Cherepashchuk 2003). In a close binary with an orbital period shorter than 1–2 days, the companion of a synchronously rotating Wolf–Rayet star could be a main-sequence star, BH, or NS. Due to the uncertainty in the limiting orbital period, the rate of such events remains fairly uncertain, and is presently estimated as $\sim 10^{-4}$ per year (Bogomazov et al. 2007).

The most popular model for short GRBs was suggested by Paczynski (1986), and supposes that, under the action of gravitational radiation, the merger of two NSs in a binary will lead to the formation of a massive, compact accretion-decretion disk around the more massive NS after the disintegration of the less massive NS (Fig. 4). The rate of such events in the Galaxy is $\sim 10^{-4}$ per year (Tutukov and Yungelson 1994). It is noteworthy that only short GRBs are detected in E galaxies, which is consistent with this scenario, since the time for the merger of two NSs is specified by the binary semimajor axis at the time of its formation, and can vary over a wide range: 10^7–10^{10} years (Tutukov and Yungelson 1994).

Conclusion

A broad range of possible scenarios for SNIa explosions in the course of evolution of close binary systems presented here (Fig. 1) and our simulations of the evolution of some types of binaries lead to the conclusion that virtually all the scenarios

could result in SNIa explosions at observed rates of 10^{-4}–0.003 per year per Galaxy. The merger of binary degenerate carbon-oxygen dwarfs whose total mass exceeds the Chandrasekhar limit currently remains the most attractive scenario. This scenario can also explain the possible delay of the explosion relative to the star formation over a broad time interval of 10^7–10^{10} yrs. The fact that the exploding CO dwarf is of an approximately critical Chandrasekhar mass explains the observed similarity of SNIa light curves. Preliminary estimates of the rate of such events are close to the observed values. Note, however, that the physics of the complex processes occurring between the merger of the degenerate dwarfs and the SNIa explosion remains now essentially unstudied, both theoretically and observationally.

The possibility that the pre-supernova degenerate dwarfs surrounded by massive carbon-oxygen disks, probably with very rapid and intense stellar winds, have rather extended lifetimes poses the actual observational problem of identifying such objects among hot stars, analogous to the hot cores of planetary nebulae, with spectra that are similar to those of C type Wolf–Rayet stars in the absence of helium. They also may manifest themselves as soft X-ray sources. Search for such objects is an important task of modern observational astrophysics.

References

Barris B. and Tonry J. (2006) ApJ 637, 427.
Bianchini A., Tamburini F. and Johnson P. (2006) astro-ph/0602157.
Bogomazov A., Lipunov V. and Tutukov A. (2007) ARep 51, 308.
Camilo F. and Rasio F. (2005) Binary Radio Pulsars, San Francisco, p. 147.
Cincarini G., Flore F., Della Valle M. et al. (2006) The Messenger 12, 54.
Dahlen T., Strolger L. and Riess A. (2004) ApJ 613, 189.
Della Valle M., Panagia N., Padovani P. et al. (2005) ApJ 629, 750.
Deng J., Kawabata K. and Ohyama Y. (2004) ApJ Lett. 605, L37.
Di Stefano R. and Kong A. (2003) ApJ 592, 884.
Gurevich L. and Lebedinskij A. (1946) Vestn. Leningrad. Univ. Nos 4–5, 53.
Hoyle F. and Fowler W. (1960) ApJ 132, 565.
Iben I. and Tutukov A. (1984) ApJSS 54, 335.
Iben I. and Tutukov A. (1985) ApJSS 58, 661.
Iben I. and Tutukov A. (1991) ApJ 370, 615.
Immler S., Brown P. and Milneebal P. (2006) ApJ Lett. 648, L119.
Kahabka P. and van den Heuvel E. (2006) Compact X-Ray Sources, Cambridge, Cambridge Univ. Press, p. 461.
Kitaura F., Janka H. and Hillrbrandt W. (2006) AAp 450, 345.
Lanz T., Telis G., Andard M. et al. (2004) ApJ 619, 517.
Lundqvist P., Mattila S., Sollerman J. et al. (2006) astro-ph/0309006.
Martin R. and Tout C. (2006) MNRAS 373, 255.
Masevich A.G. and Tutukov A.V. (1988) Evolution of Stars: Theory and Observations (Nauka, Moscow) [in Russian].
Matsubayashi T., Yamazaki R., Yonetoke D. et al. (2005) Progr. Theor. Phys. 114, 983.
Nelemans G., Napiwotzki R., Karl C. et al. (2005) AAp 440, 1087.

Oliveira A., Steiner J. and Cieslinski D. (2003) MNRAS 346, 963.
Orio M. (2006) ApJ 643, 844.
Paczynski B. (1986) ApJ Lett. 308, L43.
Scannapieco E. and Bildstein L. (2005) ApJ Lett. 629, L85.
Sullivan M., LeBorgne D., Pritchet C. et al. (2006) ApJ 648, 868.
Tutukov A.V. and Cherepashchuk A.M. (2003) ARep 47, 386.
Tutukov A.V. and Chugaj N.N. (1992) SvA Lett. 18, 242.
Tutukov A.V. and Fedorova A.V. (1989) SvA 33, 606
Tutukov A.V. and Fedorova A.V. (2007) ARep 51, 291.
Tutukov A.V. and Yungelson L.R. (1976) Astrofizika 12, 342.
Tutukov A. and Yungelson L. (1994) MNRAS 268, 871.
Tutukov A.V. and Yungelson L.R. (2002) ARep 46, 667.
Wheelan J. and Iben I. (1973) ApJ 186, 1007.