An object that defies stereotypes: X-ray observations of SBS 1150+599A, the binary nucleus of PN G135.9+55.9

G.Tovmassian[1], J.Tomsick[2], R.Napiwotzki[3], L.Yungelson[4], G.Stasińska[5], M.Peña[1] and M.Richer[1]

[1] Institute of Astronomy, Universidad Nacional Autonoma de México. gag,richer@astrosen.unam.mx, miriam@astroscu.unam.mx
[2] University California Berkeley, USA jtomsick@ssl.berkeley.edu
[3] University of Hertfordshire, UK r.napiwotzki@herts.ac.uk
[4] Institute of Astronomy, RAS, Russia lry@inasan.ru
[5] Observatoire de Meudon, France grazyna.stasinska@obspm.fr

Summary. We present X-ray observations of the close binary nucleus of the planetary nebula (PN) PN G135.9+55.9 obtained with the XMM satellite. The nebula is the most oxygen-poor PN known to date and is located in the Galactic halo. It is known to harbor a close binary nucleus of which only one component can be observed in optical-UV range. New X-ray observations show that the invisible component is a very hot compact star. This finding allows us to reconstruct the immediate past of the object and predict its future. The parameters of the binary components we determine strongly suggest that the precursor was a symbiotic supersoft X-ray source that finished its life by Roche lobe overflow. PN G135.9+55.9 is an excellent candidate for a future type Ia supernova.

Key words: Planetary Nebula; Close, Interactive Binary, Symbiotic Stars; Super Soft X-Ray Source

1 Introduction

SBS 1150+599A was identified as a planetary nebula (PN) in [15] and subsequently designated as PN G135.9+55.9. The object is unusual and is renown for its extremely low oxygen content [15, 2, 9, 13]. It is also located far and above the Galactic plane, which places it among a handful of known halo PNe. Direct images obtained by [10, 2] and a study of dynamics of the nebula [11] confirmed its PN identification, but did not make its explanation easier. Another, if not unusual but outstanding feature of the PN is that it harbors a close binary system, only one component of which is observable in the optical and UV [16]. The far-UV observations by FUSE established a temperature range for that visible component of 110 000 - 120 000 K. The lower limit of this range was established by a minimum temperature needed to produce the [Ne V] emission line, while the upper limit was deduced from a continuum fit of atmosphere models to the observed data [16]. The extremely high temperature coupled with high *log* g led us to assume that the opt/UV component was the central star of planetary nebula (CSPN), i.e. the post-AGB star that lost its envelope and was the source of its ionization. Péquignot & Tsamis [9] claimed that the ionizing star must be hotter in order to increase the oxygen abundance to more common levels ([O/H]≈ -0.9 instead of [O/H]≤ -2.2). It was an extreme solution: to justify a temperature of 120 000 K [16] a higher extinction correction than estimated for the direction of PN G135.9+55.9 is required. To resolve this controversy, we [8] obtained photometric light curves of the binary core of PN G135.9+55.9. The orbital period of the system is 3.919 hr, and to explain the double-humped shape of the light curve, one should invoke a Roche-lobe filling opt/UV component. Additionally, the depths of the minima in the light curve are uneven, which in turn assumes that the visible component should be irradiated by an even more energetic (hot) source. The dynamics required that this invisible component must be another compact object of at least $0.85 M_{\odot}$ [8].

Here we report the analysis and results of X-ray observations of SBS 1150+599A, the close binary core of PN G135.9+55.9 made with orbital telescope XMM-*Newton* and make use of publicly available HST UV-data.

2 Observations and spectral energy distribution (SED)

On 2006 Nov 1, a 25 ksec exposure of SBS 1150+599A was obtained with XMM-*Newton*. We reduced the observations using the latest version of SAS7.0. The object was detected with XMM with a count rate of 0.035 c/s in the PN detector, 0.0029 c/s in the MOS1 detector, and 0.0048 c/s in the MOS 2 detector. SBS 1150+599A appears to be emitting only very soft photons, the absolute majority of which were registered in a narrow range between 0.1 to 0.3 keV. This soft end of spectral range suffers calibration problems [14], but the extracted spectra in all three detectors are highly consistent with each other and are well-described with a black-body (BB).

For a better understanding of the nature of the object and comprehensive fit of the SED we also use the UV data obtained by HST in 2003 (Obs. ID #9466, PI Garnavich). Here, we use the continuum fit to the stellar spectra of the object obtained by STIS in near and far UV ranges. The STIS spectrum helps to fill the gap between optical and extremely far UV data obtained previously with FUSE. More importantly it eliminates the large uncertainty regarding extrapolation of the interstellar extinction law in the FUSE range and in general provides a more reliable flux calibration. Thus, we have observational data continuously covering the whole spectral range from about 10 000 to 900Å.

The SED over a wide range of frequencies from infrared (IR) to X-rays is presented in Fig 1. The optical and UV data can be fitted with a single black body (BB), while, for the X-rays, a second BB with much higher temperature is required. The discovery of a second, hotter component in the system means that we do not need to artificially elevate the extinction towards SBS 1150+599A in order to justify the presence of an ionization source of at least 110 000 K. Therefore in a revision of previous results reported in [16] we apply a regular extinction in this direction E(B-V)=0.029 [12] and fit the observed points with two BB using a χ^2 method. One of the possible solutions is presented in Fig. 1. Other solutions with comparable

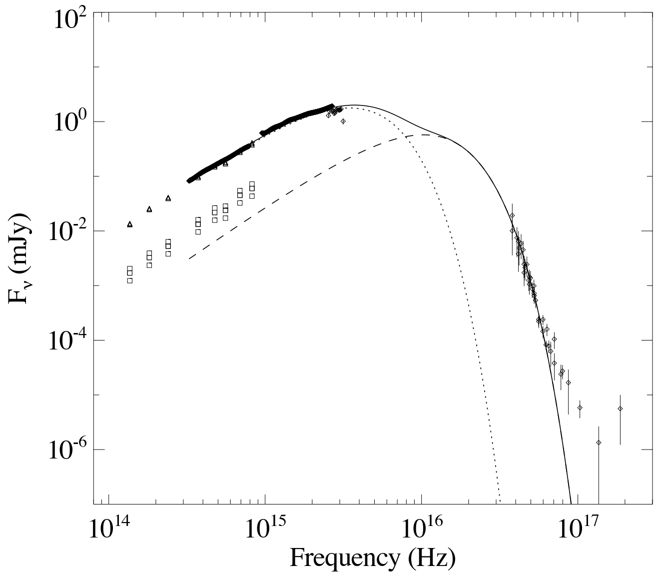

Fig. 1. Spectral energy distribution of SBS 1150+599A. Open circles with error bars are X-ray data. Filled and open diamonds are optical & UV data. The observed data are fitted with two black bodies presented with dotted & dashed lines and their sum by a solid line. The open triangles and open squares are SED of opt/UV and X-component respectively calculated by *Nightfall* for a number of solutions. They all are adjusted to the flux of opt/UV component. The discrepancy between *Nightfall* and double BB fits can be explained by lack of consideration of irradiation, geometry and effects of limb-darkening etc., in BB fitting. The solutions with much hotter X-component produce a larger discrepancy and are ruled out.

χ^2 are viable by increase of the temperature/decrease of size of the X-ray component, due to some excess of emission at the high-energy end of the spectrum. We explain below why we chose the solution with the lower temperature. According to this fit the opt/UV component has a temperature of $\approx 58\,000$ K and ratio of the radius to the distance $(r/D)_{opt/UV} = 3.8 \times 10^{-13}$, while the X-ray component has $T_X = 170\,000$ K and $(r/D)_X = 5.6 \times 10^{-14}$.

3 Parameters and the nature of the system

As the next step, we may try to determine binary system parameters, making use of the radial velocity (RV) curve and lightcurves in different colors. The rough knowledge of component's temperatures greatly improves our chances of finding other parameters of the system correctly. For this purpose we use a binary modeling code *Nightfall* provided by R. Wichmann.[6] The program allows fitting a large number of

[6] http://www.hs.uni-hamburg.de/DE/Ins/Per/Wichmann/Nightfall.html.
Nightfall is based on a physical model that takes into account the nonspherical

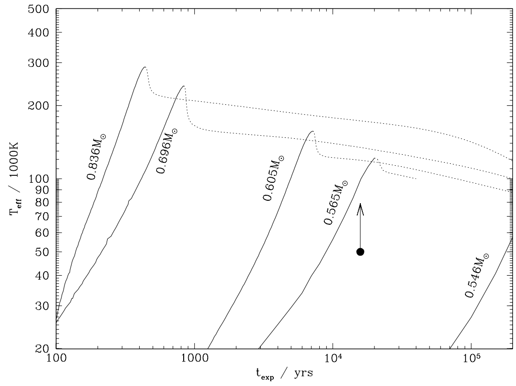

Fig. 2. Evolution tracks of low mass post-AGB stars according to [1]. The place of opt/UV component of SBS 1150+599A is marked by an arrow.

unknown parameters of the system: total mass, mass ratio of components, size of the components measured in fractions of corresponding Roche lobe, temperatures and separation of the system components. As an input for fitting we provided RV curve as measured in [16] and light curves in three colors (roughly corresponding to *U, B, R* described in [8]). Setting all parameters free forces the program immediately to seek solutions in a high mass stellar binary ($> 20M_{\odot}$). However we know for sure that the system is comprised of compact objects (WD-like) so the total mass should hover around $1.4M_{\odot}$. Fixing the total mass and temperature(s) of the components narrows the number of possible solutions, but a variety of different configurations result in a similarly good fit to the data. Therefore, additional constraints are necessary to pin down the correct composition of SBS 1150+599A.

One of the most important parameters to know are the masses of the components. We derive the mass of the opt/UV component from the fact that it is the envelope-shedding component on its track from AGB to WD. According to [1], a core of post-AGB star can reach temperatures $\geq 55\,000$ K in a reasonable time ($<$ a few $\times 10^4$ yr) only if it mass exceeds $0.56M_{\odot}$ (Fig 2). On the other hand we can evaluate the upper limit to the mass of opt/UV component from the consideration of common envelope (CE) evolution. In an 3.9 hr Pop. II binary, a $0.56M_{\odot}$ visible component may descend from AGB star that had ZAMS mass 0.9-1.1 $M_{\odot}$. Formation of a double degenerate with given orbital period through common envelope requires a certain combination of the binding energy λ and CE expulsion efficiency $\alpha_{\rm CE}$, e.g. [19]. We searched solutions for a range of progenitor masses using code [4] like in [17]. The grid of solutions is presented in Fig 3. The mass of the opt/UV component progenitor should not exceed $1.1M_{\odot}$, provided that SBS 1150+599A is Pop. II object, and it is not a strange invader captured by merging of a satellite galaxy. Fig 3 shows that this results in $M_{\rm opt/UV} < 0.58M_{\odot}$. These mass limits cor-

shape of stars in close binary systems, as well as mutual irradiance of both stars, and a number of additional physical effects, like albedo or limb darkening. *Nightfall* can handle a large range of binary star configurations, including overcontact (common envelope) systems, eccentric orbits, surface spots and synchronous rotation, and the possible existence of a third star in the system.

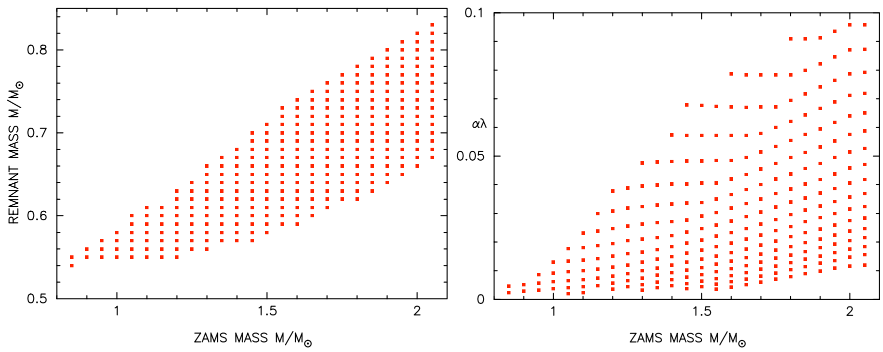

Fig. 3. Possible combinations of initial and final masses of opt/UV component of SBS 1150+599A (left panel) and corresponding $\alpha\lambda$ combinations of binding energy λ & expulsion efficiency $\alpha_{\rm CE}$ that result in orbital period of 3.9 hr (right panel).

respond to $\alpha_{\rm CE}\lambda = 0.01 - 0.02$, which is not unreasonable for stars with relatively large cores and tenuous envelopes.

We also can establish the lower limit for the mass of the X-ray component. Apparently the X-ray component is a WD remnant of a star, which was more massive than the progenitor of opt/UV component and has evolved through its AGB phase much earlier. The system most probably passed through the first CE phase and for a certain time appeared as a symbiotic system, see, e. g., [7]. In the symbiotic phase, the X-component could accrete mass at a high rate ($\sim 10^{-7} M_\odot$/yr) and manifest itself as a supersoft X-ray source (SSS), see, e. g. [5]. The accreting WD in such systems gets heated to extremely high temperatures by steady nuclear burning of accreted matter at their surface. Only accretors with $\rm M_{wd} > 0.7 M_\odot$ reach temperatures high enough to be detected as SSS [18]. The estimate of amount of matter accreted during symbiotic phase varies ([6, 7, 3]), but at least 0.1-0.15$M_\odot$ must be accumulated as a result. Therefore, we can assume that the total mass of the system is very close to or exceeding the Chandrasekhar limit.

Introducing these additional constraints to the *Nightfall*, we find the best solutions describing the light and radial velocity curves at the same time. The parameters of the system deduced by our analysis are presented in the Table 1.

Table 1. The parameters of binary components of SBS 1150+599A.

	opt/UV-component	X-component
M ($M_\odot$)	0.565	0.85 ($\rm M_{tot} = 1.41 M_\odot$)
R ($\rm R_\odot$)	0.40 – 0.48	0.16 – 0.05
T (K)	65 - 57 000	165 – 245 000

Corresponding fits to the RV and light curves are presented in Fig 4. The best fits are achieved with inclination angle $i = 50^\circ \pm 4$. The wide range of values in the right column of Tab. 1 indicates that similarly good fits can be obtained with a variety

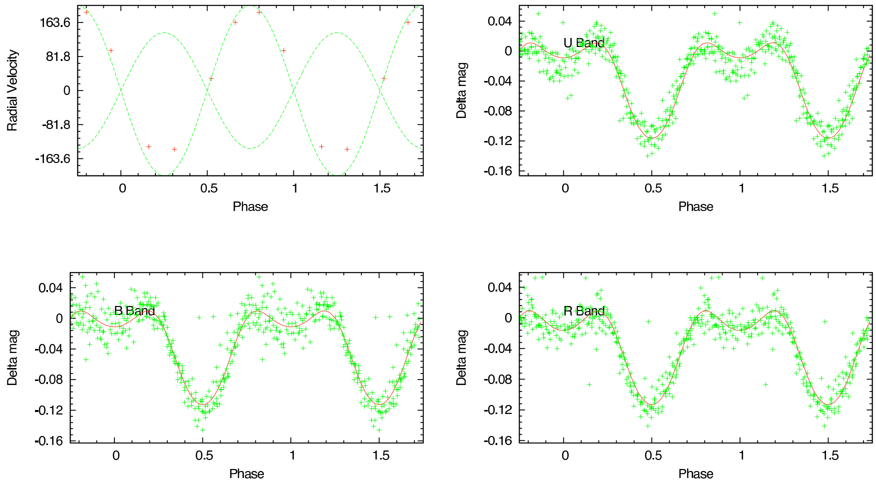

Fig. 4. Simultaneous fits to RV and light curves in three colors by *Nightfall*. The parameters of the system deduced from χ^2 fits are presented in Tab 1

of temperature/radius combination for the X-component. What matters for the fits is the luminosity of X-component to ensure certain irradiation of the Roche-lobe filling opt/UV-component. Thus, the X-ray component may be cooler and larger or hotter and smaller. But, regardless of the uncertainties of the XMM calibration and the double blackbody fitting to the SED, the correct solution is a rather cool and large X-ray component, because the flux ratio of the components should obey the ratio calculated by *Nightfall* for the Raleigh-Jeans tail and presented in Fig 1 by open triangles for the opt/UV and by the open squares for X-ray component. An extremely hot solution clearly deviates from the presented set of solutions. However, even a hot solution requires a size obviously larger than an ordinary WD. It confirms the suggestion that the X-component underwent a period of intense accretion and is surrounded by a shell-like atmosphere, heated by the surface burning.

4 Conclusions

New X-ray observations coupled with the previous UV and optical spectral energy distribution reveal a second, previously undetected component, of the close double degenerate binary core of PN G135.9+55.9. It appears to be a WD that has grown in size from accreted material in a previous symbiotic/SSS stage and heated by a steady nuclear burning on its surface. The discovery of the X-ray component adds another unprecedented feature to the already unique characteristics of the object, but at the same time helps to explain its nature. According to some scenarios, double degenerate compact binaries, progenitors of SNIa are formed as a result of two common envelope phases, which helps to remove significant amounts of angular momentum and bring the remnants of the binary system components close enough to

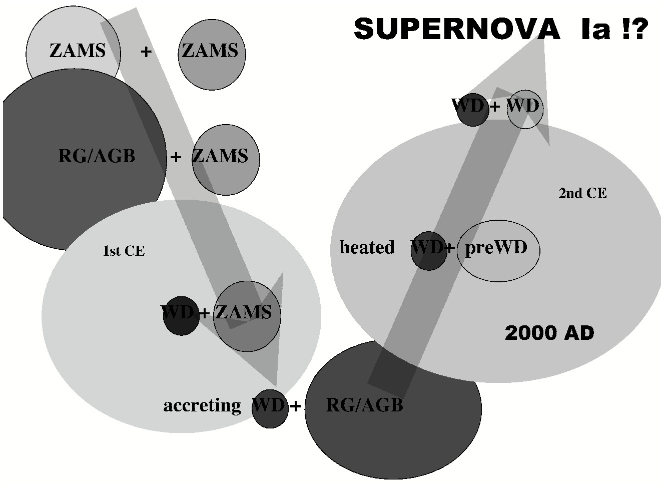

Fig. 5. Schematic evolutionary trajectory of SBS 1150+599A. The current state of the object is marked by 2000AD.

merge in a Hubble time. We suggest that in rare cases these systems pass through a symbiotic stage and show up for a short time as supersoft X-ray sources. A schematic evolutionary scenario for such systems is presented in Fig 5. Currently, we detect a PN formed as a CE released by opt/UV-component. But its ionization is due to the extreme UV photons from both components of the binary system, which means that the oxygen abundance should be revised. SBS 1150+599A remains, however, one of the rarest objects of its type, observed as a PN, heated by its extremely hot binary core, with an extreme chemical composition, located in the very outskirts of the Galaxy. Its observation over a wide range of wavelengths allows insight into one of the peculiar phases of evolution that lasts only a short time and thus is difficult to catch.

Acknowledgement. GT & JT acknowledge NASA grant NNX07AQ12G , GT is also funded by CONACyT. LY is supported by "Origin and Evolution of Stars and Galaxies" Program and RFBR grant 07-02-00454. We appreciate expertise and macros rendered by J.Wilms for XMM data reduction.

References

1. Bloecker, T. 1995, A&A, 299, 755
2. Jacoby, G. H., Feldmeier, J. J., Claver, C. F., Garnavich, P. M., Noriega-Crespo, A., Bond, H. E., & Quinn, J. 2002, AJ, 124, 3340
3. Hachisu, I. 2002, The Physics of Cataclysmic Variables and Related Objects, 261, 605

4. Hurley, J. R., Pols, O. R., & Tout, C. A. 2000, MNRAS, 315, 543
5. Kahabka, P. 2006, Advances in Space Research, 38, 2836
6. Korreck, K. E., Kellogg, E., & Sokoloski, J. L. 2007, American Institute of Physics Conference Series, 924, 903
7. Lü, G., Yungelson, L., & Han, Z. 2006, MNRAS, 372, 1389
8. Napiwotzki, R., Tovmassian, G., Richer, M. G., Stasińska, G., Peña, M., Drechsel, H., Dreizler, S., & Rauch, T. 2005, Planetary Nebulae as Astronomical Tools, 804, 173
9. Péquignot, D., & Tsamis, Y. G. 2005, A&A, 430, 187
10. Richer, M. G., Tovmassian, G., Stasińska, G., Jameson, R. F., Dobbie, P. D., Veillet, C., Gutierrez, C., & Prada, F. 2002, A&A, 395, 929
11. Richer, M. G., López, J. A., Steffen, W., Tovmassian, G. H., Stasińska, G., & Echevarría, J. 2003, A&A, 410, 911
12. Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, ApJ, 500, 525
13. Stasińska G., Tovmassian G. H., Richer M. G., Peña M., Napiwotzki R., Charbonnel C., Jamet L., 2005, IAUS, 228, 323
14. Stuhlinger, M., et al. 2006, The X-ray Universe 2005, 604, 937
15. Tovmassian, G. H., Stasińska, G., Chavushyan, V. H., Zharikov, S. V., Gutierrez, C., & Prada, F. 2001, A&A, 370, 456
16. Tovmassian, G. H., Napiwotzki, R., Richer, M. G., Stasińska, G., Fullerton, A. W., & Rauch, T. 2004, ApJ, 616, 485
17. van den Besselaar, E. J. M., et al. 2007, A&A, 466, 1031
18. Webbink, R. F. 2001, Evolution of Binary and Multiple Star Systems, 229, 309
19. Webbink, R. F. 2007, ArXiv e-prints, 704, arXiv:0704.0280