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Diffuse ionizing radiation in nebular envelopes of symbiotic novae V1016 Cyg and HM Sge

M. Skulskyy[1], B. Melekh[2] and O. Buhajenko[2]

[1] *Department of Physics, Lviv Polytechnic National University, 79013, Lviv, Ukraine, (E-mail: mysky@polynet.lviv.ua)*

[2] *Department of Astrophysics, Ivan Franko National University of Lviv, 79005, Lviv, Ukraine, (E-mail: bohdan.melekh@lnu.edu.ua)*

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Abstract. The ionizing structure of the nebular envelopes of the symbiotic novae V1016 Cyg and HM Sge were determined using Ferland's photoionization code *Cloudy* upgraded by our method *DiffRaY* for a detailed calculation of the diffuse ionzing radiation. Our calculations are based on the optimal photoionization models, obtained previously for these objects using the standard code *Cloudy* that takes into account the diffuse ionizing radiation using an *outward only approximation*. In the present paper we compare the results of the photoionization modelling of V1016 Cyg and HM Sge nebular envelopes performed using both detailed and *outward only* methods. It was shown that the approximate fast *outward only* method can be used for the modelling of these objects.

Key words: symbiotic — novae — photoionization modelling

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1. Introduction

Most researchers (see, for example, Sanad (2017); Arkhipova et al. (2015); Parimucha et al. (2001); Eyres & Bode (2001); Rudy et al. (1990); Schmid & Schild (1990); Muerset et al. (1991); Muerset & Nussbaumer (1994)) are adopting the following model of the symbiotic novae: a hot white dwarf (WD) and cold red giant that lost its matter due to the stellar wind and accretion of the matter onto the hot component. Most probably, both V1016 Cyg and HM Sge contain an evolved cool giant of the Mira type and a WD accreting from the giant's wind. They are classified as symbiotic novae because they showed one nova-like eruption in the past. In the present work we investigate the nebular envelopes of the symbiotic novae V1016 Cyg and HM Sge using photoionization modelling (PhM) methods. The spherical symmetry for the nebular envelope with the white dwarf in its center was adopted. The real shape of these objects can deviate from the spherical one, but at present details of such deviations are unknown with required precision due to a compact envelope size relatively to the observer. The binary system is also non-spherical, but we suggest that this is not important for modelling because the size of the binary system is significantly smaller than the one of nebular envelope. This nebular envelope consist of matter ejected during nova explosion(s). Of course, it can also be mixed with the wind material from the cool red giant. It must be noted that in our models the nebular envelope has an inner radius. It means that between the binary system and the nebula matter is absent. Thus, under such assumptions, the above mentioned mixing of the wind material with envelope is possible only during a nova explosion. In such binary system the role of main ionizing source for the nebular envelope belongs to the hot star and, maybe, to the accretion disk. The calculation of models stops at the ionization front (where T_e drops below 4000K), because emission lines arise within an ionized part of the nebula (the calculated intensities of these lines are used to compare with the corresponding observed data).

Emission line spectra of these symbiotic novae are similar to the ones for planetary nebulae envelopes. It allowed us to perform the photoionization modelling of these objects in our previous paper (Holovatyi et al., 2019) using the semi-empirical density distribution law obtained by Golovatyi & Malkov (1992) from analysis of the isophote maps of planetary nebulae. The radial ditribution of the gas density was approximated by equation (6) from Golovatyi & Malkov (1992). If we put optimal values (7) from the above paper to this approximating equation, we obtain the following expression for description of the radial density distribution within the nebula:

$$n_H(r) \ = \ \frac{x^2\left(1+3e^{-1.2x}\right)}{\left(x^2-1\right)^2+0.36r_c^{-0.43}x^2}DP, \tag{1}$$

where r is the distance from the center of the nebula (and from the ionizing source) to the modelling layer of the nebula, $x = r/r_c$, r_c is the characteristic radius that is close to the position of maximum of the radial hydrogen density distribution, the so-called density parameter $DP \equiv A/r_c^2$, and A is a parameter characterizing the mass-loss rate by the star into the stellar wind. If we assume $r = r_c$ in expression (1), then we obtain the expression for $n_H(r_c)$ determination as a function of parameters DP and r_c. Because the values of $n_H(r_c)$ and DP were determined during a search of optimal models of V1016 Cyg and HM Sge in the paper by Holovatyi et al. (2019), the value of r_c can be directly determined from this expression.

In Holovatyi et al. (2019) we have demostrated the similarity of the diagnostic electron density distribution in these objects over ionization potentials of the corresponding ions, emitting in the corresponding ionization zones, to the the radial distribution defined by the above mentioned semi-empirical density distribution law. Therefore, in Holovatyi et al. (2019) we performed the photoionization modelling using the density distribution representation from Golovatyi & Malkov (1992).

In Holovatyi et al. (2019) we used our three stages method (Melekh et al., 2015) based on Ferland's photoionization code *Cloudy v08.00* (Ferland,

2008) to search for the optimal photoionization models for nebular envelopes of V1016 Cyg and HM Sge. The optimal models were found using the so-called *outward only* approximation that is also a default method for calculation of diffuse ionizing radiative transfer in the code *Cloudy* (Ferland, 2008). The *outward only* method is fast and, thus, very good for the search of the optimal photoionization models (such a search requires the calculation of thousands of photoionization models). But in Buhajenko & Melekh (2018) we showed that in the case of the inhomogenious distribution of matter the usage of the *outward only* approximation sometimes can be incorrect, because it causes (*sometimes*) incorrect reproducing by the model of the emission lines in the outer part of the nebular envelope. Therefore it is necessary to be sure that our optimal models, obtained in paper Holovatyi et al. (2019), are correct. To solve this task, in the present paper we recalculated the photoionization models for V1016 Cyg and HM Sge with values of input parameters obtained as a result of optimizing PhM in Holovatyi et al. (2019) using a detailed method (Buhajenko & Melekh, 2016) for calculation of the diffuse ionizing radiative transfer. For this purpose we used the code *Cloudy* (Ferland, 2008) upgraded by our method (Buhajenko & Melekh, 2016) for calculation of the diffuse ionizing radiation in a detailed way. Then we compare resulting models with the ones obtained previously by Holovatyi et al. (2019) using the *outward only* approximation.

2. Detailed method for calculation of diffuse ionizing radiative transfer

For a precise PhM calculation of diffuze ionizing radiation, the so-called *Detailed method* should be used. In this method equations for diffuze ionizing radiative transfer should be solved across all directions with the subsequent integration over all directions (see details in Buhajenko & Melekh (2016, 2018)). However, the usage of such approach to ionization-recombination, energetic and statistical equilibrum equations is very time-consuming even for modern powerful computer clusters. To avoid this problem the approximate methods (*outward only* or *on the spot*, see details in Ferland, 2008) for a diffuse ionizing radiative transfer calculation are usually used. To accelerate the *Detailed method* in Buhajenko & Melekh (2016, 2018) we have proposed to use gradual decreasing of an integration step until the required precision be achieved. Also, the procedure for a diffuse ionizing radiative transfer calculation in our approach is developed as a separate code *DiffRaY* [1] that does not require any implementation in the photoionization code. It just needs the emission line and continuum emissivities spatial map of diffuse radiation calculated by the photoionization code at the first global iteration step (over all modelling volume) as well as an opacity map. The initial emissivities map of diffuse ionizing radiation can be calculated using

[1] The code DiffRaY and its description can be downloaded from http://old.physics.lnu.edu.ua/depts/KAF/DiffRay/

one of the above mentioned approximate methods, or it can be simply neglected (to adopt zero values for diffuse emissivities). As in Holovatyi et al. (2019) for PhM we used Ferland's code code *Cloudy* (Ferland, 2008).

Table 1. The input parameters of photoionization models obtained in Holovatyi et al. (2019) as a result of the optimimal photoionization model search for nebular envelopes of V1016 Cyg and HM Sge.

Input parameters	V1016 Cyg	HM Sge
D [pc]	1521	1273
log L_*[erg/s]	37.50	38.13
log $T_{ef}[K]$	5.128	5.087
log $n_H(r_c)$[cm^{-3}]	6.502	6.607
log(DP)	7.210	7.333
log r_{in} [cm]	14.41	14.93
log He/H	-1.095	-0.963
log N/H	-4.107	-3.776
log O/H	-4.035	-3.524
log Ne/H	-4.748	-4.197
log S/H	-5.153	-4.290
log Ar/H	-6.061	-5.292
$Dust\ factor$	0.438	1.290

In Table 1 the values of input parameters of photoionization models obtained in Holovatyi et al. (2019) as a result of the optimimal photoionization model search for nebular envelopes of V1016 Cyg and HM Sge are given. These parameters characterize the distance D from the Earth to the objects, the energy distribution in the spectrum of the central star that is the main source of the ionizing radiation (luminosity L and effective temperature T_{ef}), the hydrogen density $n_H(r_c)$ at the characteristic radius r_c, the density parameter DP (see above the description of Eq. 1), the internal radius r_{in} of the nebular envelope, the relative abundances of chemical elements, and the $Dustfactor$ for dust grains abundance adopted by default in the code *Cloudy*.

As in Holovatyi et al. (2019) all models were calculated in spherical symmetry and their calculations were stopping at the ionization front (where T_e drops below 4000K). We used these data for PhM of these objects based on the *Detailed method* for calculation of diffuse ionizing radiative transfer. For our purpose in the present work the global iterations convergence accuracy of 2% was adopted during a detailed calculation of diffuse ionizing radiative transfer using code *DiffRaY*. Covergence was achived after the third global iteration for both models of the the above objects. Also, it must be noticed that values of distances in Table 1 are smaller than those given in Muerset et al. (1991); Muerset & Nussbaumer

(1994). In these papers the distances to V1016 Cyg and HM Sge were determined using a period-luminosity (PL) relation that is used in the cases where a Mira is present in a symbiotic system. We determined the distances using optimized photoionization modelling (OPhM) method (see description of the method in (Melekh et al., 2015)). During OPhM the distance is a free parameter, and main observed parameters that are responsible for determination of its value are the angular size of the ionized nebular envelope and the observed flux in Hβ emission line. We suppose that for such peculiar objects as V1016Cyg and HM Sge the difference in results obtained by OPhM- and PL-methods should be considered in future investigations. The aim of the present paper did not include this task.

3. Results, analysis and conclusions

In Figs. 1 and 2 the radial distibutions of the electron temperature and density as well as [O III] 5007Å and [O III] 4363Å lines emissivity, obtained during PhM of nebular envelopes of V1016 Cyg and HM Sge using the *Outward Only* approximation as well as the *Detailed method*, are shown. Also in these figures there are shown zoom-ins of the nebular region containing the ionization front where the differences caused by the usage of different methods for calculation of diffuse ionizing radiative transfer, are maximal. As it was expected, the volume of the ionized nebular environment in the case of the *Detailed method* usage is a little bit smaller, because in this case the ionizing radiation is propagating in all directions, not in the outward only one as in the corresponding approximate method. The similar results were obtained in our previous works Buhajenko & Melekh (2016, 2018) for planetary nebulae envelopes and HII regions.

As it was mentioned above, in our models the nebular envelope has the inner radius r_{in} (between the binary system and the nebula the matter is absent). Eq. (1) was obtained by Golovatyi & Malkov (1992) on the basis of analysis of isophote maps of 10 real nebular objects under the assumption of their spherical symmetry. This equation has the maximum and the density decreases relatively to it in both directions (outward and inward). Such a radial hydrogen density distribution causes a similar distribution of the electron density N_e. The deviations of N_e from the hydrogen density distribution can be caused only by the presence of heavy elements in the nebula, which are the additional sources of electrons during photoionization. It can be seen that the character of the N_e radial distribution in the case of HM Sge differs from the one for V1016 Cyg. While in the case of the V1016 Cyg optimal model we see that this distribution is very similar to the one for $n_H(r)$ defined by expression (1), the maximum of the N_e distribution in the optimal model for HM Sge is very close to the inner radius r_{in} of the nebular envelope. This result was obtained because r_{in} was a free parameter during OPhM and it can reach the values larger than r_c. We suggest that such 'freedom' for variation of r_{in} is good, because it allows us to change slightly the character of the radial density distribution in the nebula

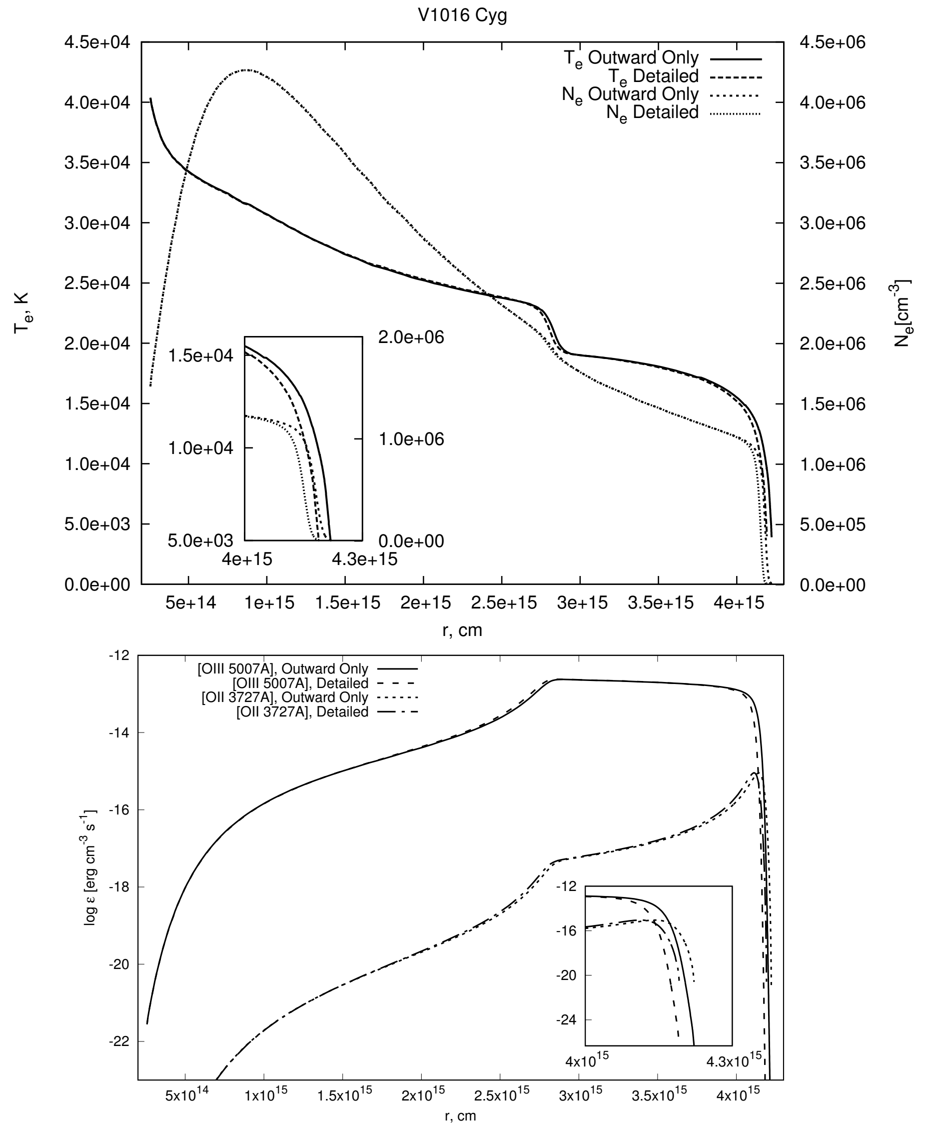

Figure 1. Comparison of the radial distributions of the electron temperature T_e and density N_e (top) as well as emissivities ϵ in [O III] and [O II] emission lines (bottom) obtained by our PhM of the V1016 Cyg nebular envelope using the *Outward only* approximation and the *Detailed* method for calculation of diffuse radiation field. Results are very similar (see the text for details).

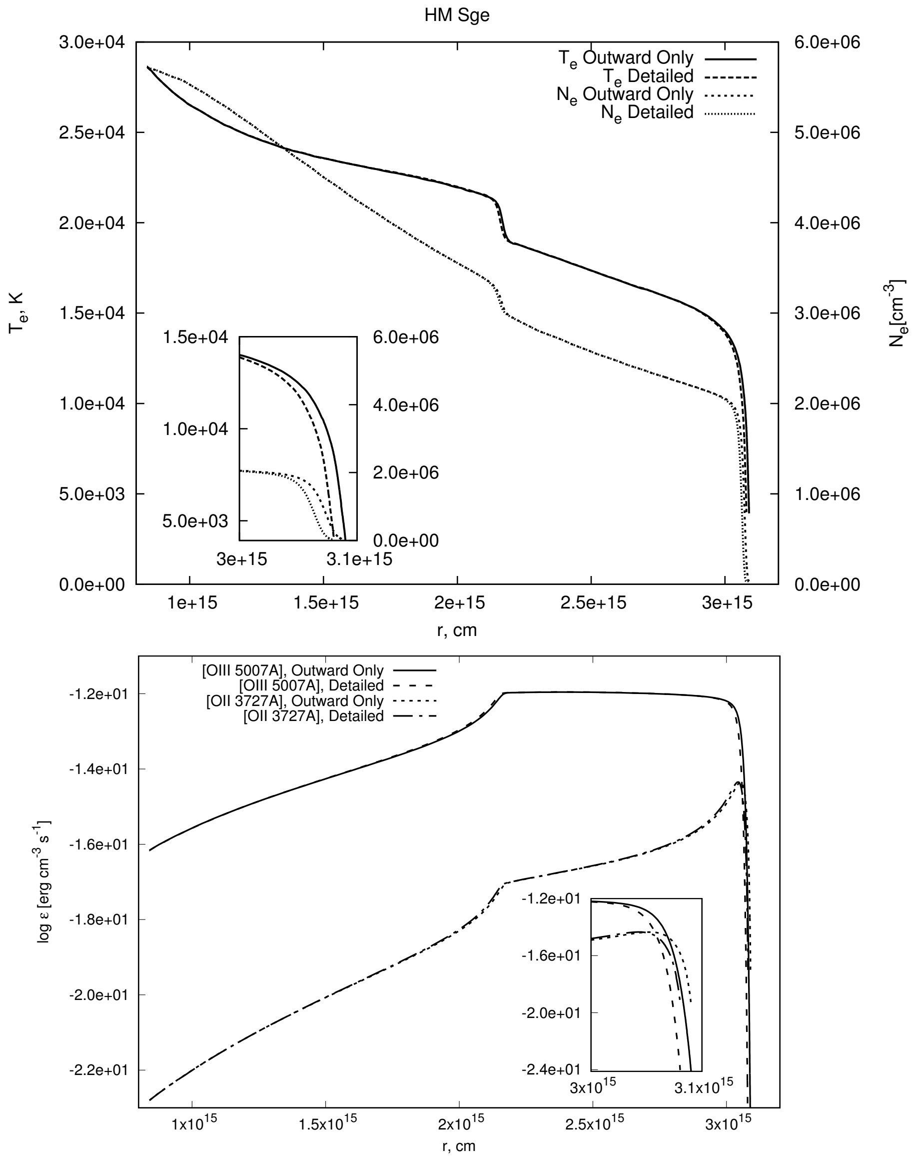

Figure 2. Comparison of radial distributions of the electron temperature T_e and density N_e (top) as well as emissivities ϵ in [O III] and [O II] emission lines (bottom) obtained by our PhM of the HM Sge nebular envelope using the *Outward only* approximation and the *Detailed* method for calculation of diffuse radiation field. Results are very similar (see the text for details).

Table 2. Comparison of the synthetic emission line spectra of nebular envelopes of V1016 Cyg and HM Sge obtained in Holovatyi et al. (2019) as a result of the search of the optimal photoionization model using the approximate *Outward Only* method, with results of PhM with the same optimal input parameters but using the *Detailed method* for calculation of diffuse ionizing radiative transfer. Deviations of these values obtained using the *Outward Only* approximation from the ones calculated using the *Detailed method* were determined using absolute values of parameters (not in a logarithmic scale).

Model of object:	V1016Cyg			HMSge		
Parameter	Outward Only	Detailed method	Δ^*, %	Outward Only	Detailed method	Δ^*, %
$\log L(\mathrm{H}\beta)$	30.546	30.543	-0.7	30.910	30.907	-0.7
[O II]λ3727/H_β	0.001	0.001	0.0	0.002	0.002	0.0
[O III]λ5007/H_β	1.791	1.791	0.0	3.791	3.807	0.4
[O III]λ4959/H_β	0.593	0.593	0.0	1.254	1.259	-0.3
[O III] λ4363/H_β	0.283	0.285	1.1	0.766	0.775	-0.5
He I λ4471/H_β	0.023	0.023	0.0	0.034	0.034	0.0
He I λ5876/H_β	0.088	0.089	0.0	0.134	0.135	0.0
He II λ4686/H_β	0.420	0.428	1.9	0.559	0.557	-0.4
[N II] λ6548/H_β	0.008	0.008	0.0	0.009	0.009	0.0
[N II] λ6584/H_β	0.022	0.022	0.0	0.025	0.025	0.0
[N II] λ5755/H_β	0.022	0.022	0.0	0.038	0.038	0.0
[S III]λ9532/H_β	0.131	0.130	-0.8	0.038	0.038	0.0
[S III]λ9069/H_β	0.052	0.052	0.0	0.583	0.580	-0.5
[S II] λ6716/H_β	-	-	-	0.001	0.001	0.0
[S II] λ6731/H_β	-	-	-	0.003	0.003	0.0
[S II] λ4070/H_β	0.021	0.021	0.0	0.117	0.116	-0.9
[S II] λ4078/H_β	0.006	0.006	0.0	0.029	0.029	0.0

$^*\ \Delta = (OutwardOnly - DetailedMethod)/DetailedMethod$

during a search for the optimal photoionization model. The maximum within the radial density distribution can be caused by the shock wave that has created during a nova explosion. We think that obtained from our photoionization modelling the radial density distributions of matter contain the information that can be useful in future hydrodynamical simulations of V1016 Cyg and HM Sge evolution, which will allows us to explain the differences between their nebular characteristics.

It must be noted that a jump (or rapid decreasing) of T_e and N_e values within radii of $(2.7-2.9)\times10^{15}$cm in models of V1016 Cyg and $(2.1-2.2)\times10^{15}$cm in the ones of HM Sge are still present in results obtained using the *Detailed method*. As it was shown in Holovatyi et al. (2019) this jump separates the inner He^{++} zone from the outer He^{+} one. It is caused by radiative transfer of both direct and diffuse ionizing quanta in these objects and, probably, it is an important feature that can be used in the future to develop new methods for investigation of radial density distributions in such nebular environments using observed (integral over sightline) emission line intensities. From Figs. 1 and 2 it can be concluded that the He^{++} zone is also a little bit smaller in the case of *Detailed method* usage during PhM.

The decrease of the whole ionization volume of the nebular environment, as well as ionization zones of various ions, in the case of the usage of a more precise method for calculation of diffuse ionizing radiative transfer during PhM of these objects, led to the decrease of integral values of emissivities in emission lines. But how does it impact on the nebular integral emission line spectrum in the case of models of V1016 Cyg and HM Sge? To answer this question we gave in Table 2 the integral H_β luminosities and relative intensities for some important emission lines, obtained during PhM using the *Outward Only* approximation as well as the *Detailed method*. It can be seen from Table 2 that deviations of PhM results obtained using the approximate *Outward only* method from the ones calculated using the *Detailed method* are less than 2% for V1016 Cyg and less 1% in the case of HM Sge. Thus, these deviations are within the adopted precision for convergence of global integration (2%) and therefore we have concluded that the usage of the fast approximate *Outward only* method in Holovatyi et al. (2019) allowed us to obtain correct results which can be used in the future for more detailed investigations of symbiotic novae V1016 Cyg and HM Sge.

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