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Nebulae around precataclysmic binary systems

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Abstract. The structure of nebulae surrounding precataclysmic binary systems is described. It is noted that all features of nebulae ejected in the evolution of binary systems are inherent in them. The values of β (the pole/equator density ratio), α (the steepness of the angular density gradient), and i (the angle of inclination to the line of sight) have been determined. The small value of β and also some characteristic features of nebulae and central stars point to strong concentration of matter towards the orbital plane of the central star and also to the fact that the formation of a common envelope in most cases is likely to have occurred when the primary component of the central system was at the red giant stage.

Key words: JSM: planetary nebulae: structure — stars: cataclysmic variable — stars: evolution — binaries: general

1. Nebulae around precataclysmic binaries

There is an inhomogeneous group of binary systems that contain a white dwarf (WD) or a hot subdwarf and a low-mass late-type star of the lower part of the main sequence. The group includes all types of cataclysmic variables which are semidetached and interacting systems, and also their detached analogues that are named precataclysmic variables (PCV). The name itself suggests the idea of their evolutionary status.

A single way of formation of WD is presently known, that is, sequential evolution of a red giant. However, the size of a red giant is much bigger than that of the above mentioned systems. For this reason, it is believed that such systems form as a result of evolution of broad pairs with periods to a few hundred days. When the more massive component fills its Roche lobe and reaches the red giant stage, it begins to intensively lose matter. Since a deep surface convective zone is being developed in red giants, then, in response to the mass loss, further expansion of the star will take place. That is, the mass transfer will proceed in a dynamical mode.

The second component, a low-mass red dwarf, is submerged in the outer layers of the giant. Being of low mass, it has a longer time of internal thermal relaxation. That is why, it cannot accrete such a great amount of matter and, accordingly, of energy and angular momentum. This leads to loss of stability and, probably, to its destruction. The created common envelope will strongly resist the motion of the red dwarf. As a result, the orbital energy and the angular momentum will be transferred to the envelope. The red dwarf will spiral towards the core of the red giant, the white dwarf, until the components merge or ejection of the envelope occurs. In the latter case a planetary nebula with a double nucleus forms. Such separated systems must be rather numerous. However, they are difficult to detect, first of all because of their faintness since, in contrast to cataclysmic variables, accretion sources of energy are lacking in them. It is obvious that for a PCB to be formed, the progenitor broad system ought to have had a great mass ratio, $q = M_1/M_2$.

The phenomena related to the duplicity of the central stars and the morphology of nebulae ejected by close binary systems have been studied in a large number of papers of different authors. It is shown in them that the matter ejected by the giant must predominantly concentrate in the orbital plane of the binary system. The result of evolution in a common envelope and the initial morphology of the nebula depend on the evolutionary state of the primary star (the common envelope originated at the stage of AGB or red giant) and on the mass of the secondary. To explain the variety of forms of planetary nebulae, a model of interacting winds is suggested. Besides, the form of the nebula is defined by contrast of density between the equator and polar regions and by interaction with the interstellar medium.

Bond and Livio (1990) noted a number of peculiarities inherent in planetary nebulae ejected in the course of evolution of binary systems: 1) no nebulae with multiple envelopes and halo were found; 2) as a rule, they have a low surface brightness; 3) cases of interaction with the interstellar medium are frequent (more frequent than in nebulae with a nucleus of a single star). Besides, according to the investigation of Iben and Tutukov (1989), one could expect differences in the chemical structure between planetary nebulae ejected by single and binary stars since the ejection of a common envelope discontinues nuclear evolution of the internal parts of the red giant.

The lifetime of planetary nebulae is about 10^4 years. This is why, binary systems observed in them have only recently emerged from the common envelope and are very young. We will further be interested in precataclysmic binary systems and the possibility of their transformation to cataclysmic variables. Table 1 gives a list of planetary nebulae the nuclei of which are PCB, together with the names of the stars and some of their characteristic properties. In most systems the companions of the white dwarf are low-mass red dwarfs which have no time to markedly evolve during the Hubble time. More massive components of early spectral classes evolve faster, and the system will undergo, at least, one more phase of the common envelope. This will result not in a cataclysmic variable but in a binary degenerate or a system of some other type.

Tweedy 1 The nebula was detected in the lines H_α and [OIII], while it is not seen in the wide band, 6000 – 7000 Å (Ferguson et al., 1981; Liebert et al., 1995; Bond, 1999). Its diameter is about $3'$, the rate of expansion is approximately 18 km/s. In H_α this is a low-contrast blurred structure of nearly round shape. In the lines [OIII] the structure is visible more distinctly: asymmetric arches of different degree of blurring and a bubble blown up by the wind from the north-west side. The shape of the nebula suggests interaction with the interstellar medium.

NGC 2346 This is a typical bipolar nebula of butterfly shape. It looks like that in the lines H_α, [NII] and [OIII], while in the lines HeII it looks almost round with the brightness concentrated towards the centre. A tore of dense ionized gas is clearly seen around the central star. The brightness of the central star has begun to change since 1981, which is due to the appearance of dust clouds that occasionally obscure it. Costero et al. (1986) believe that the occurrence of dust clouds is associated with fragmentation of the central tore. Schaefer (1985) considers that the final helium flash has begun.

NGC 6826 The bright central part of the nebula has a round shape and is surrounded by a wide round halo with a noticeable filamentary structure. The internal part of the nebula contains a tore of dense luminous gas and two bright ejections, apparently, from the polar regions. The ratio of the radii of the halo and of the bright part of the nebula is $\gtrsim 5.3$ (Jewitt et al., 1986).

IC 418 A slightly elliptical nebula. Its image in the lines H_α and [NII] has a noticeable brightening at the edge, which may be due to interaction with the interstellar medium. The images in the lines [OIII] and HeII look nearly round and homogeneous, with a bright central part. This can be especially well seen in the images in the line HeII. The images and expansion velocities in [OIII] and [HeII] are smaller than in H_α and [NII]. This suggest that the expansion occurs in the space that has already been passed by the fronts of H and NII, that is why, there is almost no interaction with the interstellar medium.

A 41 This is an approximately ellipsoidal envelope with the axes $19''$ and $13''$. There are two diametrically opposite bright arches in the envelope. They are, possibly, a torroidal structure ejected in the orbital plane and visible at a rather high inclination, while a weaker elliptical envelope may be material of low density ejected outside the orbital plane (Grauer & Bond, 1983). It seems to us that the fainter parts of the envelope are fragments of the same torroidal structure blown by the wind coming from the polar regions of the primary component.

DS 1 Unfortunately, there is no good image of this nebula. Bond & Livio (1990) presented an image of the inner part of the nebula in the line [OIII]. They consider that it can be characterized as a late stage of an elliptical nebula threaded with bubbles in the east-west direction. It seems to us that a similar structure may arise at simultaneous ejection in the equatorial and polar directions and when the system is visible at a small angle. In a small-scale white-light image (Drilling, 1983) a faint almost round nebulous spot is noticeable around the central star. It is difficult to say whether it is an extended halo surrounding the brighter central part of the nebula, or it is a poor visibility of the nebula in the white light, which is not infrequent. Its shape is not at variance with the statement of the late stage of the elliptical nebula.

A 63 The image of the nebula in the H_α line is of irregular shape with irregular distribution of luminous matter. Bond & Livio (1990) believe that this is the late stage of an elliptical nebula. Since the total eclipse is observed in the central part of the star, visible matter is then outside its orbital plane.

A 46 The image of the nebula in the lines H_α and [OIII] is a nearly round structure with inhomogeneous distribution of luminous gas. Bond & Livio (1990) think that the shape of A 46 may be affected by interaction with the interstellar medium. We believe that in the case of A 46, the action of the inhomogeneous wind may also be assumed.

K 1–2 It is seen on the images in H_α and [OIII] lines (Bond & Livio, 1990; Bond, 1999) that the central part of the nebula of inhomogeneous brightness is surrounded with a faint extended halo of elliptical shape. The halo is extended in the north-south direc-

Table 1:

Usual name	Designation PK	Central star	β	α	i(degrees)		
					1	2	3
Tweedy 1	-	BE UMa	0.3-0.4	1.3	76		60
NGC 2346	215.6+3.6	V651 Mon	0.1	4	60	50	45
NGC 6826	83+12.1	BD+50°2869	0.1	2		49	30
IC 418	215-24.1	BD-12°1172	0.5	1		60	30
A 41	9+10.1	MT Ser	0.4	1		37	45
DS 1	-	KU Vel	0.1	1	60	40	35
A 63	53-3.1	UU Sge	0.5	1	$\lesssim$90		70
A 46	55+16.1	V477 Lyr	0.4	1		90	90
K 1–2	253.5+10.1	VW Pyx	0.2	1		60	40
A 35	303+40.1	BD-22°3467	0.6	0.7	15	50	20–50
LoTr 5	339+88.1	BD+26°2405	0.4-0.5	1		30	20
NGC 6543	96+29.1	BD+66°1066	0.5	1		45:	30
HFG 1	136+5.1	V664 Cas	0.4	1		20	
-	-	BZ Cam	0.5	1		30	

Notes: the inclination angle of the orbit plane of the central star (1); nebula inclination angle determined from the axial ratio (2) and from the models (3)

tion. The most remarkable feature of the bright part of the nebula is a jet-like structure moving away from the centre. It can also be seen in the line [NII] (Lutz & Lame, 1989). Possibly, there is a faint jet in the opposite direction.

The existence of jets suggests the presence of a disk. Since the central star is a binary system, the disk might have originated in mass transfer between the components. However, there is no evidence of their interaction. The jets possibly originated as a result of bipolar hydromagnetic winds similar to those in protostellar objects. For this, however, an initial disk is necessary (Pudritz & Norman, 1986).

Numerous indications are currently available that many post-AGB stars, even single, expand asymmetrically and often eject jet-like structures. Doesn't it mean that K 1–2 is a very young nebula in which the phase of common envelope has only recently ended?

A 35 This is a large nebula of very low and inhomogeneous surface brightness (Jacoby, 1981; Tweedy & Kwitter, 1996). On the red charts of the Palomar Sky Survey two parallel lines are seen south of the central star. A parabolic structure, which is absent in H_α, is distinct in the image in λ5007 Å [OIII]. The central star is situated at the focus of the parabola, and the direction of its proper motion coincides with the axis of the parabola.

The unusual shape of A 35 is explained by interaction of the rapidly moving central star (of the binary system) with the interstellar medium. Here the system loses matter in the form of fast wind. Structures formed under such conditions have been studied by Weaver et al. (1977). A 35 is one of the oldest nebulae. Its age has been estimated at $1 \div 2 \cdot 10^5$ years (Jacoby, 1981).

Lo Tr 5 This is a small bright point-symmetrical nebula. No signs of interaction with the interstellar medium have been revealed. This is the most high-latitude galactic planetary nebula.

NGC 6543 The nebula is of complex structure. In the lines H_α and [OIII] one can distinctly see a halo, the size of which corresponds to the maximum size of the structure of dense gas. In the lines [NII] and [OI], jet-like structures located along the axis of the complex structure are noticeable.

HFG 1 This is an old highly-excited nebula, very bright in [OIII]. The south-east part of the nebula consists of three bright diffuse regions enveloped with nearly round rings. In the east, between the rings and the diffuse regions, filaments are seen. The north-west part of the nebula is of very low surface brightness and inhomogeneous. The observed structure of the nebula points to active interaction with the interstellar medium.

BZ Cam The nebula around this binary star consists of two components: a large homogeneous one well visible in the H_α line and a filamentary structure with a leading compression wave to the south. This compression appeared as a result of motions of the star which has a high spatial velocity, 125 km/s. The leading density wave can also be well seen in the line λ5007 Å [NIII]. However, a wide homogeneous nebula is not seen in [NIII] (Greiner et al., 2001). Spectral observations have shown that intensive ejection of matter continues in the system (Woods et al., 1990; Patterson et al., 1996). This is also suggested by the unstable light curve.

BZ Cam itself belongs to nova-like systems, i.e. it emerged from the common envelope being already a cataclysmic variable, therefore it is of particular interest to us.

A study of morphology of the nebulae from Table 1 has shown the following: the signs of interaction with the interstellar medium are distinctly exhibited in 7 out of 14 nebulae; the multiple envelope is seen only in one nebula (NGC 6826); the overwhelming majority of nebulae are of low surface brightness. Thus, the characteristic features of nebulae ejected by binary systems and noted by Bond & Livio (1990) are reliably traced. It can be added to this that in about half the nebulae torroidal structures are observed, which are likely to be formed as a result of predominant concentration of ejected matter in the orbital plane of the binary system (NGC 2346, 6543, 6826, A 41, DS 1, IC 418?, K 1–2?). In many central stars intensive outflow of matter is still in progress, which is indicated by the line profiles of type of PCyg in their spectra and by the unstable light curves.

As noted above, the original morphology of the nebula depends on the evolutionary state of the primary star and on the mass of the secondary component. The frequent occurrence of torroidal structures suggests that formation of the common envelope would often occur when the primary component of the system was at the red giant stage. Accordingly, in nebulae with torroidal structures, which surround precataclysmic binaries, one can expect low contrasts of density between the pole and equator and greater distances between the system components, if the masses of the secondary components are equal as compared to nebulae without such structures.

To check the former statement, we made use of the models of Zhang & Kwok (1998). Table 1 presents the values of β, α, i found for the nebulae under study, where β is the ratio of the gas density at the pole and at the equator, α is the steepness of the angular density gradient, i is the angle of inclination to the line of sight. As β decreases, the nebula stretches in the polar direction, and in the equatorial regions casps begin to develop. The shape of the nebula becomes increasingly bipolar or butterfly type. It is seen from Table 1 that all nebulae are characterized by small β. Only in one $\beta > 0.5$. Whereas, there are no preferable values in the distribution in β in ordinary nebulae. In terms of α and i, our nebulae do not differ from normal (Zhang and Kwok, 1998). The angle i is determined from the model and from the ratio of the radii of the nebula, where it is possibly compared with the inclination of the orbital plane of the central binary star. In some cases, the discrepancies are great, but in most cases they are within the determination erors.

Unfortunately, the testing of the latter statement presents difficulties because of the lack of observational data. As an example, compare A 35 and NGC 2346. Their central systems have the secondary components close in mass. In the nebula NGC 2346 with a torroidal structure, the central system has the orbital period $P = 15^{\rm d}.991$ and one of the greatest separation of the components, $\sim 40\,R_{\odot}$. In the nebula A 35, without a visible torroidal structure, the orbital period of the central system is $P = 0^{\rm d}.765$ and the distance between the components is $\sim 4\,R_{\odot}$.

Thus, the above-said and the data of Table 1 verify the assumption that nebulae surrounding precataclysmic binaries frequently originate at the red giant stage of the primary component of the central star, which causes strong concentration of the ejected material in the orbital plane of the system.

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