Late Stages of Binary Evolution

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CLOSE-BINARY NUCLEI OF PLANETARY NEBULAE

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Abstract.

Close-binary planetary-nebula nuclei (PNNs) provide direct evidence for occurrence of a common-envelope phase in binary-star evolution. Their descendants are V471 Tauri-type detached binaries, cataclysmic binaries, and possibly Type I supernovae. Thirteen close-binary PNNs are now known from periodic photometric or radial-velocity variations, or from composite optical/UV spectra. At least 10% of PNNs are close binaries, a fraction more than sufficient to account for the formation of all of the cataclysmic variables in the solar neighborhood. The Abell 35-type binary PNNs, a class with three known members, contain rapidly rotating, chromospherically active late-type primary stars along with extremely hot companions detected with the *IUE* satellite.

1. The Significance of Close-Binary PNNs

In this paper we will review the results of observational searches, based primarily on photometry and/or ultraviolet spectroscopy, for close binaries among planetary-nebula nuclei (PNNs). Close-binary PNNs are of significance for several reasons:

1. They provide direct evidence for the existence of a common-envelope phase in binary evolution (see Bond and Livio 1990 and references therein, and the forthcoming review paper by Livio and Iben 1992). In this scenario, one starts with a binary of fairly wide separation, large enough for the more massive component to evolve to the red-giant or asymptotic-giant-branch (AGB) stage before beginning to transfer mass to its companion. Since in this case the response of the primary star to mass loss is to expand, and since the mass transfer shrinks the orbit, an extremely rapid mass transfer ensues, leading to the entire system being engulfed in a common envelope. The ensuing spiral-down may lead to ejection of the common envelope, leaving a close binary surrounded by a planetary nebula that is ionized by the hot core of the former red giant.

2. It is thus possible that binary-star interactions may be responsible for formation of a significant fraction of all planetary nebulae.

3. The probable descendants of close-binary PNNs are detached white-dwarf/red-dwarf pairs (like V471 Tauri) and, ultimately, the cataclysmic binaries. Some cataclysmics may undergo a second common-envelope episode, leading to double-degenerate binaries and, possibly, Type I supernovae. Thus the close-binary PNNs provide a crucial link relating wide binaries to a variety of exotic systems.

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2. Discovery Techniques

Three observational criteria have been used to discover close binaries among the central stars of planetary nebulae (PNe).

1. Photometric variability. CCD techniques have made it possible to obtain accurate photometry even for central stars in bright PNe. In very close systems containing one hot component, there can be significant heating of one hemisphere of the companion star. Thus, even in systems insufficiently inclined for actual eclipses to occur, quite large optical variability can still be present. An example is the central star of HFG 1, whose CCD light curve shows sinusoidal variability with an amplitude of over 1 mag at optical wavelengths (Bond et al. 1988). (HFG 1 also shows variable high-excitation emission lines, which vary with orbital phase over the 14-hour period in a sense in agreement with their arising by reprocessing on the heated face of the cool companion star.)

2. Radial-velocity variations. The 16-day binary period of the nucleus of NGC 2346 was first revealed by its radial-velocity variations (Méndez and Niemela 1981) (although it is also, episodically, a photometric variable).

3. Composite spectrum. Several apparently close-binary PNNs have been discovered because they contain a late-type star that dominates the optical band, along with a second, hot component revealed by the *IUE* satellite. We propose to call these objects the "Abell 35-type" PNNs after the first such system to be discovered with *IUE*.

The 13 PNNs that are known or reasonably suspected to be close binaries are listed in Table 2 of Bond and Livio (1990). There are 9 "heated-hemisphere" or "reflection-effect" binaries (including the eclipsing nuclei of Abell 46 and Abell 63) with orbital periods ranging from 2.7 hours (Abell 41) to 2.9 days (Sp 1); the spectroscopic/photometric binary NGC 2346 mentioned above; and three Abell 35-type systems.

3. Morphologies of Planetary Nebulae Ejected from Close Binaries

This subject has been discussed in a published paper by Bond and Livio (1990), who give references to theoretical studies. Here we mention here only a few important points.

In general, one expects a density contrast in a PN ejected from a common-envelope binary, in the sense that a higher density of ejected matter is expected in the equatorial plane as compared with the polar directions. The highest density contrast is expected for ejection from the envelope of a first-ascent red giant, and a lower contrast when the ejection is from an AGB star. A fast wind from the hot component of the central binary can then modify the structure set up by the envelope ejection.

Inspection of CCD emission-line images of the 13 PNe with close-binary PNNs shows that about half of them do show the expected butterfly or elliptical morphologies. However, Sp 1 is nearly perfectly round; we can understand its morphology only if it is in fact a toroidal structure seen nearly pole-on. At least three more nebulae show evidence for modification of their structure by interactions with the interstellar medium, while K 1-2 is very peculiar, with evidence for jet ejection from the central object.

4. Incidence of Close-Binary PNNs

The frequency of occurrence of close binaries among the nuclei of PNe can be estimated from the searches for photometric variability which, as outlined above, have revealed 10 objects with photometric periods of less than 3 days. We are aware of four major photometric surveys, those of Drummond (1980), Drilling (1985), Bond and Grauer (1987), and Bond and Ciardullo (ongoing), in which about 108 distinct objects have been observed.

From these statistics we can conclude that of order 10% of randomly selected PNNs are photometrically detectable binaries.

Zuckerman and Aller (1986) have pointed out that $\gtrsim 80\%$ of all PNe have non-spherical morphologies. This raises two possibilities:

1. Non-spherical (elliptical and butterfly) PNe can be ejected from single stars, possibly through the influence of stellar rotation or non-interacting binary companions.

2. Or a large fraction of PNe may in fact have been ejected from interacting binaries, which have either coalesced or have remained so wide after the interaction that they do not exhibit detectable photometric variations. It is worth noting that Méndez et al. (1988a,b), using an argument based on surface gravities and effective temperatures, have suggested that the central stars of EGB 5 and PHL 932 are coalesced binaries.

5. Close-Binary Nuclei as Progenitors of Cataclysmic Binaries

Light-curve solutions for the two known eclipsing PNNs, those of Abell 46 (Bond, Kaluzny, and Grauer, in preparation) and Abell 63 (Bond, Liller, and Mannery 1978), show that the companions of the hot components have radii typical of K-M dwarfs. A discussion of the reflection effect in Abell 41 (Grauer and Bond 1983) showed that the companion again has the radius of a dM star. Thus the properties of these systems are exactly what we would expect for progenitors of cataclysmic variables (CVs), which are binaries in which a main-sequence star transfers mass to a companion white dwarf. Moreover, in the case of Abell 41, we showed that gravitational radiation alone will be sufficient to bring the stars close enough to initiate mass transfer within the next few Gyr.

In an earlier review (Bond 1989), we estimated the birth rate for close-binary PNNs in the solar neighborhood on the assumption that it amounts to about 10% of the birth rate for all PNe. This estimate shows that the birth rate is, if anything, more than enough to account for the formation of all of the CVs in the solar neighborhood.

If there is a discrepancy between the birth rates for binary PNNs and CVs, it could indicate (1) that the process of transformation of post-PNNs to CVs has not, in the age of the galaxy, had time to reach equilibrium (i.e., the post-PNNs are accumulating as detached binaries like V471 Tau), or (2) that our census of the CV population is still incomplete, perhaps because a significant fraction of them are in states of "hibernation."

6. Abell 35-Type Binary PNNs

The optical spectra of the nuclei of Abell 35, LoTr 1, and LoTr 5 reveal rapidly rotating G-K (sub)giants. Ultraviolet spectra obtained with *IUE* show that in each case the cool star is accompanied by an extremely hot ($\gtrsim 10^5$ K) companion. (References to the *IUE* discoveries are as follows: Abell 35, Jacoby and Gull 1981 and, independently, Grewing and Bianchi 1989; LoTr 1, Bond, Ciardullo, and Meakes 1989; LoTr 5, Feibelman and Kaler 1983).

Our CCD photometry of these three objects shows low-amplitude variability with periods of 3.2, 6.6, and 5.9 days, respectively. (The 3.2-day period for Abell 35 may be an alias of a 18-hour period.) We have a large data base of photometry of LoTr 1, showing that the amplitude of the periodic variation changes over timescales of months. This suggests strongly that the variability arises from starspots on the surface of the rotating, chromospherically active cool star, and that the amount of starspot coverage slowly varies.

In this interpretation, the photometric variability of the three Abell 35-type nuclei arises solely from the rotation of the cool star, and the true orbital periods remain unknown. In fact, the orbital periods could be much longer than the photometric periods, as is demonstrated by the binary star HD 128220. This object, which also contains a cool, rapidly rotating component along with a hot sdO companion, but is not surrounded by any obvious PN, has an orbital period of 871 days (Wallerstein and Wolff 1966; Howarth and Heber 1990). Clearly, the cool component of HD 128220 is rotating much more rapidly than synchronously with the orbit, and the same may well be true of the Abell 35 PNNs.

What is the origin of the rapid rotation of the cool subgiants in these systems? We can speculate that the cool stars might be main-sequence stars that were spun up by accretion while in the common envelope, and that they still remain "puffed up" (i.e., out of thermal equilibrium) for a Kelvin-Helmholtz timescale after their emergence from the common envelope. The possible relation of these objects to the rapidly rotating, late-type FK Comae stars remains to be explored.

7. Summary

1. Thirteen PNNs are known or strongly suspected to be close binaries, on the basis of periodic photometric or radial-velocity variability and/or *IUE* composite spectra.

2. These objects are probably descended from initially wide binaries that have undergone a common-envelope interaction, with accompanying drastic loss of matter and angular momentum from the system.

3. They are the ancestors of V471 Tau-like white-dwarf/red-dwarf detached binaries, cataclysmic variables, and possibly Type I supernovae.

4. About 10% of PNNs are observed to be close binaries, an incidence more than enough to account for the origin of all cataclysmic binaries.

5. The class of Abell 35 nuclei, containing rapidly rotating late-type components and extremely hot companions, presents an interesting challenge to our understanding of binary-star evolution.

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