Abstract.
It is already known that about 10% of central stars of PNe are very short-period binaries (hours to days), which are detected through photometric variations. These must have been formed through common-envelope interactions in initially wide binaries, accompanied by ejection of the envelope and its subsequent photoionization as a PN. Radial-velocity observations by ourselves and others are now suggesting that an even larger fraction of planetary nuclei may be spectroscopic binaries, making the total binary fraction very large. However, we have not as yet been able to rule out the possibility that the apparent velocity changes are actually due to stellar-wind variations. Pending follow-up spectroscopic observations with large telescopes, it presently appears plausible that binary-star ejection is the major formation channel for planetary nebulae.

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ARE MOST PLANETARY NEBULAE EJECTED FROM BINARY STARS?

In this paper, I report results of research by myself and my colleagues Orsola De Marco, Andrew Fleming, Dianne Harmer, Robin Ciardullo, Melike Afsar, and Al Grauer.

There are at least three arguments that suggest that many planetary nebulae (PNe) are ejected from binary stars:

1. A large majority of PNe have highly non-spherical or bipolar shapes. The simplest explanation of this fact would be that PN ejection occurs through common-envelope (CE) interactions, in which the more massive star in an initially wide binary evolves to red-giant dimensions and then engulfs its main-sequence companion. The ensuing spiralling down of the orbit spins up the envelope until it is ejected non-spherically, leaving a much closer binary consisting of the hot core of the red giant (which photoionizes the ejected envelope) and the companion. If there are PNe that were not actually ejected in a CE interaction, the ejection process may still be strongly influenced by a companion star, through tidal spin-up of the envelope and/or dynamo magnetic-field generation.

2. There is an observed high incidence of very close binaries among planetary-nebula nuclei (PNNi). Photometric monitoring programs have shown that ~10% of PNNi are binaries with periods of a few hours to a few days (e.g., several papers by Grauer & Bond in the 1980’s; Bond & Livio 1990; Bond 2000). Such very close systems must have emerged from CE interactions.

The final orbital period following a CE interaction depends on the efficiency with which orbital energy goes into ejecting material from the system, denoted $\alpha_{CE}$. If $\alpha_{CE}$ is high, the final orbital periods will tend to be long, but if $\alpha_{CE}$ is low, the periods will be shorter (and mergers of the cores will occur more often). Further discussion and theoretical simulations are given in the following paper by De Marco.

3. The photometric method for finding binary PNNi relies on the heating effect of the hot nucleus on the facing hemisphere of the main-sequence companion, which occurs only in very close binaries. Thus the 10% of PNNi that can be detected as binaries photometrically could be only the short-period tail of a much larger overall binary fraction. Population-synthesis studies suggest that this is in fact true for a wide range of $\alpha_{CE}$ values (e.g., Yungelson et al. 1993).

Figure 1 shows the predicted period distribution for binary PNNi from Yungelson et al. (with additional labels added by the present author) for a simulation with an assumed high value of $\alpha_{CE}$. There are three regimes labelled in the diagram: (a) At long initial periods, the system does not enter into a CE, and the period at the time a PN is visible is essentially unchanged (actually, it is slightly longer due to the loss of material from the binary); when the difference in magnitude between the components is small enough and the angular separation large enough, such systems can be seen as resolved visual binaries. A “snapshot” search for visual binaries among PNNi was carried out with the Hubble Space Telescope by Ciardullo et al. (1999), and resulted in the discovery of 10 likely physical pairs out of 113 PNNi examined. These systems are useful for determining distances to the PNe through main-sequence fitting, but a significant effect of the binarity on the morphology of the nebula is unlikely. (b) At shorter periods, around 1000 days, Figure 1 predicts a lack of binary PNNi, because such systems did enter into a CE interaction, and ended up at shorter
periods. (c) The peak on the left side of Figure 1 is due to post-CE systems, which have spiralled down to short periods. For $\alpha_{\text{CE}} \simeq 1$, we see that the photometrically detectable binaries with periods up to a few days could be only a fraction of the total, which extend up to periods of more than 100 days.

Thus the $\sim 10\%$ of all PNNi known to be binaries in the photometrically detectable regime could simply be the “tip of the iceberg” of a very large overall binary fraction. This would mean that PNe are fundamentally a binary-star phenomenon.

**TESTING THE “ICEBERG” HYPOTHESIS**

An observational test of this hypothesis requires radial-velocity (RV) measurements, in order to find the wider binaries that lack photometrically detectable heating effects.

My colleagues and I have been carrying out two spectroscopic surveys of PNNi in order to detect periodic RV variations indicating binary membership:

1. In the northern hemisphere, De Marco, Fleming, Harmer, and myself have used the 3.5-m WIYN telescope and Hydra multi-object spectrograph at Kitt Peak to monitor RV’s.
2. And in the southern hemisphere, Afsar and myself are using the 1.5-m SMARTS telescope and its Cassegrain spectrograph at Cerro Tololo.

**THE WIYN RADIAL VELOCITY PROGRAM**

With the WIYN spectrograph, we obtain a dispersion of 0.33 Å/pix and a spectroscopic resolution of $\sim 7000$, leading to an RV precision of $\sim 3$–$3.7$ km/s. Our RV monitoring was carried out from 2002 to 2004, with telescope scheduling optimized to find periods of days to months.

Results of the 2002-3 monitoring have been published by De Marco et al. (2004), and can be summarized by saying that the fraction of PNNi with variable velocities is extremely high. Specifically, 10 out of 11 PNNi with 4 to 16 measurements each have RV’s that are variable, with statistical confidence levels of 98 to 100%.

**FIGURE 1.** Theoretically predicted distribution of orbital periods among PN central stars if $\alpha_{\text{CE}} = 1$, from Yungelson et al. (1993). Added labels indicate, from left to right, systems that have emerged from common-envelope interactions, a gap where systems are absent because they have spiralled down to shorter periods, and wide systems that never entered a CE.
THE SMARTS RADIAL-VELOCITY PROGRAM

With the SMARTS 1.5-m spectrograph, observations were carried out in 2003-4, and are being analyzed by Melike Afsar as part of her PhD thesis at Ege University, Turkey. The dispersion is lower than at WIYN, 0.77 Å/pix, giving a resolution of ~2000 and an RV precision of about 10 km/s. As with WIYN, the scheduling was optimized to search for periods of days to months.

Once again, we find strong evidence for variable RV’s, in spite of the lower precision. Out of 19 PNNi with at least 5 measurements, 7 have variable RV’s with greater than 99% confidence. Reassuringly, 4 of the PNNi are in common with those in the WIYN program; all 4 were found variable in the WIYN data, and 3 of them are also variable in the SMARTS data (with the fourth also being variable at the 88% confidence level).

RADIAL-VELOCITY SUMMARY AND CAVEATS

At WIYN ($\sigma \sim 3.5$ km/s) we found 10 out of 11 PNNi to have variable RV’s, and at SMARTS ($\sigma \sim 10$ km/s) 7 out of 19 have variable RV’s.

Sorensen & Pollacco (2004) have independently carried out an RV survey with a precision of approximately 5 km/s, and found 13 out of 33 central stars to have variable RV’s (including NGC 6891, which we also find to be variable from both WIYN and SMARTS data).

Do these results prove that the binary fraction is extremely high among PNNi? Unfortunately, it is too soon to assert this conclusion.

First, the RV measurements are difficult in some PNNi, because there are few photospheric absorption lines, especially those free of nebular emission-line contamination, and the velocity amplitudes we have found are generally low. Moreover, it could be that some or many of the absorption lines contain components due to a strong stellar wind, and that variations in these winds are mimicking true RV variations. Although we did make an effort to select PNNi that are relatively free of strong winds (e.g., we discriminated against stars with strong P Cygni features in their UV spectra), variable winds remain a possible explanation for at least some of the apparent velocity variability.

Finding a periodic RV variation would greatly strengthen the binary interpretation, but unfortunately we have not as yet been able to fit a completely convincing period to any of our targets, with the possible exception of the nucleus of IC 4593, which may have a 5.088 day period, as shown in Figure 2.

The problem is that our observations are indicating RV’s that vary on a timescale as short as one day, whereas our

![Figure 2](image-url)

**FIGURE 2.** Radial velocities of the central star of IC 4593, measured with the WIYN 3.5-m spectrograph and phased with a period of 5.088 days. If these variations are due to true binary motion (rather than to stellar-wind variations), the mass function is $f(m) = 0.006$, implying $m_2 > 0.13M_\odot$ if $m_1 = 0.6M_\odot$. 

The solution to this problem is that our observations are indicating RV’s that vary on a timescale as short as one day, whereas our
epochs were sparsely scattered over an interval of 2-3 years. This is highly non-optimal for fitting the data with periods that now appear to be as short as a few days.

WHAT NEXT?

Based on the above results, we have concluded that the next step will be intensive spectroscopic monitoring of a few PNNi for which we have already detected RV variations, using a large telescope, high spectral resolution, and high S/N. This will allow us to distinguish between wind variations (which will produce variations in the line profiles) and true binary motion (in which the entire profile will move back and forth periodically). De Marco and I recently used 5 nights on the Kitt Peak 4-m Mayall telescope and its echelle spectrograph to carry out such observations, and the results will be reported in the future.

IMPLICATIONS OF A HIGH BINARY FRACTION AMONG PN NUCLEI

There are several interesting astrophysical implications if the binary fraction among PNNi is indeed very high. One involves the existence of PNe in globular clusters, such as the famous K 648 in M15. The post-AGB remnants of low-mass stars are expected to evolve so slowly across the HR diagram that, by the time they become hot enough to ionize an ejected envelope, the envelope would already have dissipated into space. Thus, the existence of 4 known PNe in globular clusters is difficult to understand. However, binaries can merge or transfer matter before the PN stage is reached, producing higher-mass remnants that do evolve fast enough. See Alves, Bond, & Livio (2000) for further discussion of this point.

Another point involves the existence of PNe at the bright end of the luminosity function, which are used to determine extragalactic distances. These may be descended from binaries, as discussed in a paper by Robin Ciardullo at this meeting.

Most of the classes of compact binaries are probably descended from binary PNNi via common envelopes. These include pre-cataclysmic binaries containing a red dwarf and a white dwarf, exemplified by the well-known V471 Tauri in the Hyades cluster (O’Brien, Bond, & Sion 2001 and references therein), cataclysmic variables, low-mass X-ray binaries, and SN Ia progenitors.

Knowing the overall period distribution among PNNi would help constrain the typical value of $\alpha_{CE}$, which is needed for population-synthesis calculations.

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