1. INTRODUCTION

There is reason to think that many of the central stars in planetary nebulae (PNe) may be close binaries. The evidence leading to this suggestion includes the following:

1. Photometric monitoring has revealed that about 10% of planetary-nebula nuclei (PNNi) are very close binaries, with periods of a few days up to a few weeks (e.g., Bond & Livio 1995; Bond 2000). These close binaries in PNe provide direct evidence for the occurrence of a common-envelope (CE) interaction (Paczynski 1976; Sandquist et al. 1998), in which one component of a binary evolves to giant dimensions and then engulfs a main-sequence companion; the ensuing spiral-down of the orbit ejects the CE and exposes the hot core of the red giant, leaving a close binary inside a photoionized PN.

2. Theoretical studies of the evolution of binary populations (e.g., Yungelson, Tutukov, & Livio 1993; Han, Podsiałdowski, & Eggleton 1995) predict the orbital period distribution of binary stars inside PNe to be a strong function of the efficiency, $\alpha_{CE}$, with which the orbital energy of the original system goes into ejecting material from the CE. However, a recent study (O’Brien, Bond, & Sion 2001) of the post-CE eclipsing binary V471 Tauri indicates that $\alpha_{CE} \approx 0.1$, for this one object. Figure 3b of Yungelson et al. then predicts, if this value of $\alpha_{CE}$ is applicable to most CE interactions, that the orbital periods of binaries in PNe should be distributed roughly evenly over the range 0.3–30 days. Since 10% of PNNi are already known to be binaries lying in the short-period tail that is detectable photometrically, these results suggest that a large fraction of PNNi could be longer period binaries.

3. A large majority of PNe have highly nonspherical shapes, including numerous extreme cases of strongly bipolar or axisymmetric morphologies (e.g., Zuckerman & Aller 1986; Soker 1997). The simplest explanation for these shapes would be that most PNe have been ejected through CE interactions or that the PN ejection process has at least been affected by other phenomena directly related to the presence of a companion star (e.g., tidal spin-up and/or dynamo generation of magnetic fields).

The strongest empirical test of this hypothesis of a large binary fraction would be to search for the expected population of binary PNNi with periods too long to be detected from photometric variability but detectable through radial-velocity (RV) variations. Knowledge of the overall period distribution of binary PNNi would provide strong constraints on (1) the binary properties of the parent asymptotic giant branch population and (2) the typical value of $\alpha_{CE}$, a quantity needed to predict the properties of other post-CE systems, including cataclysmic variables, low-mass X-ray binaries, and the progenitors of Type Ia supernovae.

In this Letter, we report initial results of an RV survey of PNNi, designed to detect variability on timescales of a few days up to a few months, with velocity amplitudes down to a few kilometers per second.

2. TARGET SELECTION AND OBSERVATIONS

Our spectroscopic data were taken at the 3.5 m WIYN telescope at Kitt Peak National Observatory between 2002 August and 2003 September. It is well known (e.g., Kennicutt, Freedman, & Mould 1995) that for optimum sampling of unknown periods, the observations should be spaced over an interval at least as long as the longest expected period, with the intervals between successive observations increasing according to a power series.

Since we wished to search for periods of a few days up to about 2 months, this scheduling requirement dictated use of a spectrograph that is easily available on the telescope without major instrument changes, making runs as short as one night possible. The Hydra fiber-optics bench-mounted spectrograph (Barden & Armandroff 1995), which can be put into use very quickly on the WIYN telescope by rotating the Nasmyth tertiary mirror, was thus ideal for meeting our scheduling needs.

We were awarded eight nights each in three successive semesters, with each semester’s individual nights spaced nearly
and the T2KC CCD detector, provided a dispersion of 0.33 Å pix⁻¹ and a wavelength coverage of 4050–4730 Å. The FWHM of comparison lines was typically 0.60 Å. We generally obtained a Cu–Ar comparison lamp exposure after every three stellar exposures, which was adequate because of the high stability of the bench spectrograph.

Our goal was to conduct an RV survey of a representative selection of PNNi. However, as is well known, many PNNi have significant stellar winds, raising the danger that short-timescale variations in mass-loss rate could give rise to spurious apparent velocity variations. (Note, for example, that virtually all PNNi with obvious P Cygni profiles in the ultraviolet are observed to vary photometrically on short timescales; Bond & Ciardullo 1989; Handler et al. 1997.) In order to maximize the probability of measuring center-of-mass motions of the stars, we drew up a list of targets likely to have low mass-loss rates and optical spectra dominated by photospheric absorption lines. These included stars classified as type O (e.g., by Heap 1977), sdO, B, or sdB by various authors. In order to minimize exposure times, we favored stars brighter than about 14th visual magnitude. Several candidate stars were observed but found to have few or no usable absorption lines and were thus dropped from our program.

At this writing, we have obtained useful spectra of 11 PNNi on at least four, and up to 16, different nights.

In addition to the PNNi, we obtained spectra on most nights of the well-known sdO spectrophotometric standard star BD +28°4211. This star has a spectrum similar to those of some of our program stars but is not known to be surrounded by a PN. To the best of our knowledge, this star has not been reported of our program stars but is not known to be surrounded by a PN. To the best of our knowledge, this star has not been reported of our program stars but is not known to be surrounded by a PN. To the best of our knowledge, this star has not been reported of our program stars but is not known to be surrounded by a PN.

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3. DATA REDUCTION AND ANALYSIS

We reduced our spectra with NOAO IRAF software. The dohydra task was used to flat-field, extract, and wavelength-calibrate the spectra. Excellent fits to the wavelength dispersion curve were obtained, with rms scatter of about 0.03 Å.

We measured RV shifts between normalized pairs of spectra using the cross-correlation technique implemented by the IRAF task fxcor. For each star in our sample, we initially selected the spectrum with the highest signal-to-noise ratio (S/N) as the template and cross-correlated it with the other spectra taken at different epochs. We then used these initial RV estimates to shift each spectrum to the velocity of the template and created a weighted average of all of them. This averaged spectrum, with typical S/N ≥ 100, was then used as the final template to determine the relative RV shifts between it and each of the other spectra. In the present work, we have not attempted to place the RVs on an absolute velocity scale.

The fxcor task calculates the velocity shift between two spectra by fitting the correlation with a user-selected function. Most of our PNNi have a variety of line profiles, including pressure-broadened Balmer lines as well as narrower lines from metallic species. A parabola was finally adopted as the best-fitting function.

We regard the errors in our relative velocities as arising from two sources. One is the random velocity scatter due to errors in the dispersion fit, mechanical drifts in the spectrograph, and other less easily specified effects. To estimate this scatter, we measured the relative velocities of the strong nebular [O III] λ4363 emission line of NGC 6891, based on 17 spectra. Such a sharp nebular line is expected to have a constant RV. The rms scatter of the measured relative velocities was found to be 2.1 km s⁻¹, which we take as a measure of the random velocity errors affecting all of our measurements (note that this is closely similar to the velocity scatter expected from the 0.03 Å = 2.0 km s⁻¹ dispersion of our comparison-line fits).

In addition, there is a contribution from the errors of the individual absorption-line cross-correlation fits owing to effects such as photon noise and the shapes and widths of the absorption-line profiles. The fxcor task reports a random error for each velocity shift based on the error in fitting a parabola to the cross-correlation function. For a sharp, strong emission line such as [O III] λ4363 in NGC 6891, the error reported by fxcor is negligible (<0.2 km s⁻¹) compared to the night-to-night scatter. For the absorption-line RVs of our program stars, we found that the fxcor errors are also less than the random night-to-night error estimated above, except for spectra with low S/N or with especially broad or shallow absorption lines. In our analysis below, we combine in quadrature the random error estimate of 2.1 km s⁻¹ with the random error from fxcor, in order to estimate the overall error of each RV measurement.

The stellar absorption lines most commonly encountered in PNNi in our spectral range are Hα and Hβ (often contaminated by nebular emission) as well as lines of He i, He ii, C iii, C iv, N iii, N v. When determining the cross-correlation using stellar absorption lines, we selected spectral windows so as to exclude the nebular emission lines in those objects with strong superposed emission.

4. RESULTS AND DISCUSSION

In Table 1, we present the list of stars for which we have obtained at least four good (continuum S/N ≥ 20) spectroscopic observations (see the Appendix for further comments on the individual objects). In columns (5), (6), and (7), we list the number of times each star was observed, n, the standard deviation, σ, of the ensemble of relative RV measurements, and the average error of an individual RV measurement. Each star was observed once per night, on as many nights as the weather and sidereal time permitted.

The question whether a collection of RV measurements is consistent with the hypothesis of a constant velocity is a classical problem, discussed in detail, for example, by Trumpler & Weaver (1953, p. 205). These authors recommend a standard χ² calculation, from which the reduced value, χ²/(n − 1) (given in Table 1, col. [8]), leads to an estimate of the probability that the star’s RV is variable (col. [9]; e.g., Press et al. 1986, p. 165).

Table 1 shows the startling conclusion that 10 out of the 11 PNNi that we have observed have variable velocities. Reassuringly, our control star, BD +28°4211, has a constant RV according to our statistical test (i.e., it has only a 24% probability of variability). (As Table 1 shows, the individual RV errors for BD
+28°4211 are relatively large, averaging 3.3 km s⁻¹. This is due to the relatively high gravity of this star, which gives it broader lines than our typical PNN; hence, the cross-correlation function is broader, with an attendant larger error in the velocity shifts.)

Are these RV variations due to motion in a binary system or to some other phenomenon (e.g., stellar-wind variations that modulate absorption-line profiles in a way that mimics velocity variability)? Detection of a clearly periodic velocity variation would provide strong support for binary motion. Unfortunately, owing to the poor weather that we encountered, we have only a handful of observations of each star spaced over more than a 1 yr interval. Most of our stars appear to show RV variations on timescales as short as 1 day, suggesting that their periods, if they are binaries, are relatively short. Thus, our sampling is extremely nonoptimal for period searching. We have used the Lafler & Kinman (1965) periodogram to search for periodic variability in those few cases. The results appear to be consistent with those presented recently by Pollacco (2003), who finds, in a somewhat less sensitive RV survey, that 57% of a sample of 23 PNN have variable RVs. They plan to continue our monitoring of northern-hemisphere targets, and we are currently analyzing RV data for about 30 southern-hemisphere PNN. Such observations will greatly clarify the situation. At present, it has become increasingly plausible that binary-star ejection is a major formation channel for PNe.

We are thankful for the terrific effort of the WIYN/NOAO team in supporting our project, in particular WIYN Observatory Director George Jacoby, telescope operators Gene McDougall, George Will, Doug Williams, and Hillary Mathis, and instrument specialist Chuck Corson. We thank John Glaspey for carrying out the difficult task of meeting our exacting telescope scheduling requirements. Don Pollacco provided useful information in advance of publication. O. D. is grateful to Janet Jeppson Asimov for financial support.

APPENDIX A

COMMENTS ON INDIVIDUAL OBJECTS

PHL 932.—This object is almost unique among PNN in being classified as an sDB star. Its effective temperature and surface
gravity (Napiwotzki 1999) suggest it could be a post–red giant in a binary system that underwent a CE episode (Mendez et al. 1988; Iben & Tutukov 1993). No RV variations greater than 2 km s⁻¹ were detected over an interval of 6 days by Wade (2001). Our claim of RV variability rests largely on one outlying velocity measurement, differing from the mean of the remaining eight observations by \(-8.9 \pm 2.5 \) km s⁻¹; this suggests that, if the star is a spectroscopic binary, its eccentricity is high, which would be surprising for a post-CE system.

**BD +33°2642.**—This is an extremely well-observed spectrophotometric standard star, so it is a surprise that its surrounding faint PN was not discovered until 10 yr ago (Napiwotzki 1993). Our RV measurements show a range of 15.3 km s⁻¹, well in excess of the small errors for this bright star with many usable photospheric absorption lines. RV variations of this star have also been reported by Napiwotzki et al. (2001).

**IC 4593, NGC 6210, NGC 6891.**—Our measurements of these three rather similar objects rely on absorption lines of \(\text{He} \text{II} \) at 4200 and 4541 Å, as well as the wings of the Balmer lines (the cores are contaminated with nebular emission). We find definite RV variability in all three, with total ranges of 36.4, 16.7, and 15.6 km s⁻¹, respectively. However, the nucleus of IC 4593 is variable photometrically on a timescale of hours (Bond & Ciardullo 1989), has P Cygni profiles in the UV, and shows short-timescale variations in its optical (Mendez, Herrero, & Manchado 1990) and UV (Patriach & Perinotto 1995) emission features. Mendez et al. also reported optical absorption-line RV variations in IC 4593 similar to those we report here. The other two PNNi variable photometrically on a timescale of hours (Bond & Ciardullo 1989), has P Cygni profiles in the UV, and shows short-timescale variations in its optical (Mendez, Herrero, & Manchado 1990) and UV (Patriarchi & Perinotto 1995) emission features. Mendez et al. also reported optical absorption-line RV variations in IC 4593 similar to those we report here. The other two PNNi likewise show P Cygni profiles in the UV. We therefore cannot completely rule out that the optical RV variability that we measured is due to variations in the stellar-wind mass loss.

**IRAS 19127+1717.**—This was suspected of binarity by Whitelock & Menzies (1986), because the contrast between the high excitation of the PN with the relatively cool temperature of the B9 central star suggested that the ionization source is an optically inconspicuous hot companion. We find strong evidence for RV variability, with a total range of 33.0 km s⁻¹.

**LS IV –12°111.**—This was originally discovered in the Case-Hamburg survey for luminous early-type stars and was reclassified as a post-AGB star embedded in a young PN by Conlon et al. (1993). Arkhipova et al. (2002) have reported photometric variations, and Ryans et al. (2003) suspected RV variability on the basis of three velocity measurements. We confirm definite RV variability, with a total range of 39.0 km s⁻¹.

**M1-77 and M2-54.**—These have both been reported to be photometric variables on timescales of hours (Handler 1995, 1999). We find definite RV variability for both PNNi (total ranges of 32.8 and 49.0 km s⁻¹, respectively). Although the photometric variability might suggest a connection with the wind variability discussed above for IC 4593 and similar objects, our spectra show a wealth of sharp absorption lines, and IUE spectra show no P Cygni profiles. We thus believe there is a high probability that both stars are spectroscopic binaries, although the nonperiodic photometric variability would then be left unexplained.

**A78.**—This is a prototypical born-again PNN (Iben et al. 1983; Jacoby & Ford 1983). Like IC 4593, NGC 6210, and NGC 6891, it has pronounced P Cygni profiles in the UV, so the RV variations that we find (total range 23.1 km s⁻¹) might conceivably be attributable to wind variability.

**Sa 4-1.**—This has a high-velocity wind seen as blueshifted absorption in high-dispersion IUE spectra, with relatively weak emission near zero velocity (Feibelman & Bruhweiler 1989), putting it at risk of wind variability. Our four spectra, however, show only marginal evidence for RV variation.

### REFERENCES

Acker, A., Ochsenbein, F., Stenholtm, B., Tylenda, R., Marcout, J., & Schohn, C. 1992, Strasbourg-ESO Catalogue of Galactic Planetary Nebulae (Garching: ESO)

Arkhipova, V. P., Ikonioukova, N. P., Noskova, R. I., & Komissarova, G. V. 2002, Astron. Lett., 28, 257

Barden, S. C., & Armandroff, T. T. 1995, Proc. SPIE, 2476, 56

Bond, H. E. 2000, in ASP Conf. Ser. 199, Asymmetrical Planetary Nebulae II: From Origins to Microstructures, ed. J. H. Kastner, N. Soker, & S. Rappaport (San Francisco: ASP), 115

Bond, H. E., & Ciardullo, R. 1999, in Post-AGB Objects as a Phase of Stellar Evolution, ed. R. Szczerba & S. K. Gorny (Dordrecht: Kluwer), 277

O’Brien, M. S., Bond, H. E., & Sion, E. M. 2001, ApJ, 563, 971

Paczynski, B. 1976, in IAU Symp. 73, Structure and Evolution of Close Binary Systems, ed. E. E. Eggleton, S. Mitton, & J. Whelan (Dordrecht: Reidel), 75

Patriarchi, P., & Perinotto, M. 1995, A&AS, 110, 353

Pollacco, D. L. 2003, in Asymmetrical Planetary Nebulae III: Winds, Structure, and the Thunderbird, ed. M. Meixner, J. Kastner, N. Soker, & B. Balick (San Francisco: ASP), in press

Press, W. H., Flannery, B. P., Teukolsky, S. A., & Vetterling, W. T. 1986, Numerical Recipes (Cambridge: Cambridge Univ. Press)

Ryan, R. S., I. Dufton, P. L., Mooney, C. J., Rolleston, W. R. J., Keenan, F. P., Hubeny, L., & Lanz, T. 2003, A&A, 401, 1119

Sandquist, E. L., Taam, R. E., Chen, X., Bodenheimer, P., & Burkert, A. 1998, ApJ, 500, 909

Soker, N. 1997, ApJS, 112, 487

Trumpler, R. J., & Weaver, H. F. 1953, Statistical Astronomy (New York: Dover)

Wade, R. A. 2001, in ASP Conf. Ser. 226, 12th European Workshop on White Dwarfs, ed. J. L. Provencal, H. L. Shipman, J. MacDonald, & S. Goodchild (San Francisco: ASP), 199

Whitelock, P. A., & Menzies, J. W. 1986, MNRAS, 223, 497

Yungelson, L. R., Tutukov, A. V., & Livio, M. 1999, ApJ, 418, 794

Zanin, C., & Weinberger, R. 1997, in IAU Symp. 180, Planetary Nebulae, ed. A.acerbis & S. K. Gorny (Dordrecht: Kluwer), 473

Zanin, C., & Weinberger, R. 1992, Strasbourg-ESO Catalogue of Galactic Planetary Nebulae (Garching: ESO)

Zanin, C., & Weinberger, R. 1997, in IAU Symp. 180, Planetary Nebulae, ed. A.acerbis & S. K. Gorny (Dordrecht: Kluwer), 473