Mem. S.A.It. Vol. 76, 608

Memorie della

Radial-Velocity Survey of Central Stars of Southern Planetary Nebulae

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Abstract. We have monitored selected southern-hemisphere planetary-nebula nuclei (PNNi) in order to search for radial-velocity (RV) variations. The observations have been carried out regularly since early 2003 with the SMARTS Consortium 1.5-m telescope and Cassegrain spectrograph at Cerro Tololo Inter-American Observatory, Chile. This study is a followup to an earlier survey of northern PNNi made by De Marco et al. (2004), which suggested that there is a high incidence of RV variability among PNNi. If the variations are due to motion in binary orbits, the fraction of close binaries among PNNi must be very high, suggesting that most planetary nebulae are ejected through binary-star processes, such as common-envelope interactions. We presente here the results of the southern portion of our RV survey. Preliminary results indicate that the fraction of variable RVs is also very high among southern PNNi.

Key words. Binaries: spectroscopic – planetary nebulae Stars: AGB and post AGB – Techniques: radial velocity

1. Introduction

Previous observations suggest that both single and binary planetary nebula nuclei (PNNi) can produce PNe by ejecting an AGB envelope, or through a common-envelope (CE) interaction, respectively. According to theoretical studies, many close binaries (initial orbital separation less than $\sim 1500 R_{\odot}$) should experience one or more CE interactions during their lifetimes (Iben & Tutukov 1989). The concept of CE evolution was introduced by Paczynski (1976) to explain the formation of cataclysmic variables. The existence of close binaries in PNe provides the most direct evidence for the occurrence of CE phase in the evolution of binary systems (e.g. Iben & Tutukov 1993, Rasio & Livio 1996).

Up to date, it has been reported that at least 10% of PNNi are very close binaries, with periods ranging from hours to days (Bond & Livio 1990, Bond 2000). These objects have been discovered as binaries because they exhibit periodic photometric variability (due to stellar eclipses or reflection effect).

The orbital period of a binary PNN depends on the initial orbital separation of the system and the efficiency with which the binary reduces its separation by depositing orbital energy into the CE. The efficiency pa-

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rameter, α_{CE}, has been defined (Livio & Soker 1988) as the fraction of the original energy that goes into ejecting matter. When predictions from the several population syntheses are considered with one of the recent studies made by O'Brien et al. (2001), it is seen that with a α_{CE} value of $\sim$ 0.1, the orbital periods of close binary nuclei of planetary nebulae (PNe) should range from roughly 0.3 to 30 days. This result suggests that a significant fraction of binary PNNi will have periods longer than those detectable through photometry.

On the other hand, a previous study made by Bond & Livio (1990) revealed that PNe which are known to have close binary nuclei show axisymmetric morphologies, which appear consistent with the CE scenario. As is well known, a very high fraction of PNe have nonspherical shapes, including strongly bipolar or axisymmetric morphologies.

The discussion above makes it clear that it is important to attempt searching for radial-velocity (RV) variations of binary PNNi which have periods too long to be detected using photometry. An initial study made by De Marco et al. (2004) for 11 northern PNNi showed that 10 out of 11 PNNi appear to have variable RVs. As a follow-up, we report here preliminary results from a RV survey of PNNi located in the southern hemisphere.

2. Target selection and observations

RV monitoring has been carried out since early 2003 with the 1.5-m telescope and cassegrain spectrograph, operated by The Small and Moderate Aperture Research Telescope System (SMARTS) consortium at Cerro Tololo Interamerican Observatory (CTIO). We have obtained long-slit spectroscopic data for 19 southern PNNi, listed in Table 1.

The purpose of this project is to search for RV variations on timescales of a few days up to about 2-3 months. At present, the number of RV measurements per star ranges from 5 to 47, as shown in Table 1. Most of the spectra have been obtained with a 600 line mm^{-1} grating, yielding a FWHM resolution of 2.2 Å. The dispersion is 0.77 Å pixel^{-1}, covering the wavelength range 4017–4938 Å. In order to control for spectrograph flexure, we obtained He-Ar comparison lamp exposures before and after every stellar exposure. Usually a set of three stellar exposures was obtained, in order to allow removal of cosmic rays.

Because many PNNi have significant stellar winds, we tried to choose targets such that they have low mass-loss rates and optical spectra dominated by photospheric absorption lines. Another selection effect on targets was the visual magnitude of the objects in order to minimize exposure times. Because of this, we chose stars which have visual magnitudes brighter than 14.

In addition to the PNNi, we also obtained spectra every night of at least one IAU RV standard stars, usually either 5 Ser or 6 Cet, in order to monitor the stability of our velocity system.

3. Data reduction and analysis

For the basic reduction steps for long-slit spectra, we used packages in the IRAF[1] image-processing system. After bias subtraction and flat-fielding, we extracted one-dimensional spectra, applied the wavelength calibration using the comparison exposures (typically obtaining a wavelength solution with an RMS residual of about 0.03 Å), and combined the three stellar exposures to remove cosmic rays.

RVs were determined using the fxcor cross-correlation routine within IRAF, which is based on the method of Tonry & Davis (1979). In the first pass, each spectrum of a given target was cross-correlated against one of the exposures to determine a relative RV shift. Then, each spectrum was shifted to the same relative velocity (using the IRAF routine dopcor), and all of the spectra were combined to create a super-template spectrum. For most of the stars, the super-template has a S/N $\geq$100.

Each individual spectrum was then cross-correlated against the super-template in order to derive a final relative RV for each observa-

[1] IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

Table 1. The list of program stars and radial-velocity measurements

Program Star (1)	n (2)	χ^2 (3)	σ (4)	P (5)
CRBB 1	22	1.19	9.90	0.753
Cn 1-1	22	0.88	7.37	0.381
He 2-138	20	1.95	14.24	0.992
He 2-151	9	1.81	11.97	0.930
IC 4593	26	2.42	19.28	1.000
K 2-2	15	2.67	15.62	0.999
LS IV -12°111	47	1.25	9.64	0.883
LSS 1362	16	1.28	9.95	0.796
Lo 8	21	0.65	7.22	0.124
LoTr 1	15	0.62	6.02	0.150
M 1-55	5	1.15	13.12	0.668
NGC 1360	21	1.45	12.02	0.914
NGC 1535	18	2.09	21.16	0.995
NGC 2392	12	2.79	16.60	0.999
NGC 246	28	0.75	8.78	0.183
NGC 6891	23	4.67	26.37	1.000
PHL 932	19	2.29	13.32	0.999
SaSt 2-12	8	0.31	4.35	0.048
Sp 3	9	1.81	15.42	0.929
Control Stars				
5 Ser	28	0.98	7.60	0.511
6 Cet	16	0.53	5.54	0.075

Column descriptions: (1) Program and control stars name; (2) The number of spectroscopic observations; (3) χ^2 per degree of freedom; (4) The weighted rms scatter of our RV measurements (km s^{-1}); (5) The probability that the RV is variable.

tion (including the corrections for differences in the correction to heliocentric RV).

As part of the fxcor procedure, we used fast Fourier transform (FFT) data filtering to improve the fitting to the cross-correlation function. We carried out simulations, similar to those of Pryor et al. (1988) and Armandroff et al. (1995), in order to determine the most appropriate filtering parameters, as well as to get a precise understanding of the velocity errors given as output by the fxcor task. We found that it is necessary to apply a scale factor to the errors produced by fxcor, which are a (weak) function of the S/N of the input spectra.

The errors in the RVs have 2 components: (1) those due to photon statistics as described above, and (2) those due to systematic effects (such as different placements of the star in the slit, especially if the seeing is very good, including the effect of atmospheric refraction; and possibly other causes, such as spectrograph flexure). To estimate the systematic errors, we calculated the standard deviation (SD) of the RV measurements of the standard stars (5 Ser and 6 Cet). By taking the average of both SD values obtained from these standards we found an average systematic error of ~ 8 km/s.

Through the RV calculation only the absorption lines come from stellar photosphere were used, while emission features related to nebula itself were excluded. The stellar absorption lines mostly used in our spectral range were Hδ and Hγ as well as lines of He I, He II, C III, C IV, N III and O II.

4. Results and discussions

In Table 1, we list the results for our program stars and two IAU RV standards. The columns give the names of the target stars, the number of spectroscopic observations, n, the weighted rms scatter of our RV measurements, the chi-squared per degree of freedom, χ^2, and the probability that the RV is variable, P.

The probability of variability was calculated using a standard chi-squared test, as described in Trumpler & Weaver (1953), and discussed by De Marco et al. (2004).

As shown in Table 1, about 50% of the selected southern PNNi appear to have variable RVs at greater than 90% confidence, and 37% at greater than 99% confidence. These results are similar to those of Sorensen & Pollacco (2004), who carried out an RV survey for 33 PNNi and found 40% to be variable. Our variability fraction is not as high as reported by De Marco et al. (2004), but we note that our lower RV accuracy yields a lower detection efficiency.

Are these RV variations due to the orbital motion in a binary system, or to other phenomena (e.g., stellar-wind variations that modulate the absorption-line profile)? We have used the Lafler & Kinman (1965) periodogram algorithm to search for orbital periods, but have not as yet found convincing periods for any of our targets. De Marco et al. (2004) had a similar result. In both cases the problem may be that our time sampling was not, in retrospect, optimal. Many of our targets appear to show RV variations on timescales as short as 1 day, suggesting that, if they are binaries, their periods are relatively short. Our observations, as well as those of De Marco et al. (2004), however, have covered several years and were optimized to search for relatively long periods. Thus, even if the RV variations are strictly periodic, we are badly affected by aliasing. It remains possible, of course, that the variations are not periodic. The next step should be an intensive monitoring of a few targets with high-S/N spectra, to attempt to distinguish between binary motion and line-profile variations.

At present, considering both the high fraction of very short-period binaries found through photometric monitoring, and the high fraction of RV variables found now by several groups, there is a strong suggestion that the fraction of binaries among PNNi may be very high. If so, planetary nebulae may be fundamentally a phenomenon produced by binary-star interactions.

Acknowledgements. M. Afşar thanks the Turkish Scientific and Research Council (TUBITAK-Turkey), Dr. H.E. Bond and STScI for their invaluable supports during her Ph.D. studies.

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