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# A Search for Binaries in Proto-Planetary Nebulae

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**Summary.** Planetary nebulae (PNe) and proto-planetary nebulae (PPNe) possess a bipolar structure whose formation mechanism is commonly attributed to the interaction of a binary companion. The evidence for a binary companion for PPNe is reviewed, and observational support for this model is found to be lacking. In particular, new observational results are presented from a radial velocity study of PPNe. Spectroscopic binaries allow one to sample the parameter space between close, short-period photometric binaries and distant, long-period visual binaries. In a study of 7 PPNe, no binaries are found, although all are found to vary due to pulsation. The result set a limit of  $K < 2.5 \text{ km s}^{-1}$ . Possible selection effects are examined. This result suggests that these PPNe will evolve into PNe either as single stars or as binaries with either a very low-mass or a distant companion.

**Key words:** Binaries: general – proto-planetary nebulae: general

## 1 Introduction: Why Search for Binary PPNe?

Proto-Planetary Nebulae (PPNe) display a basic bipolar structure, with axial lobes and point symmetry. This has been particularly seen in high-resolution *HST* images. Some also display an obscured equatorial region. How did this structure form?

PPNe are the objects in transition between the AGB and PN phases in the evolution of intermediate- and low-mass stars. During the AGB phase, such stars are surrounded by an expanding circumstellar envelope (CSE) of mass being lost at an increasing rate. In the PPN phase, the high rate mass loss has ended and the star is surrounded by a detached, expanding CSE. Several mechanisms have been proposed to produce the lobes (and equatorial disk or torus). These include the following:

- *A binary companion.* Such a companion can produce the lobes by (a) gravitationally focusing the mass loss into the orbital plane or by (b) tidally spinning up the PPNe so that it preferentially loses mass in the orbital plane. Each of these phenomena can produce a dense torus which then focuses the subsequent fast wind into a bipolar direction, where it evacuates the polar lobes.

- *A strong magnetic field.* In such a field, ionized material moves along field lines to produce the bipolar lobes. Such a field might be enhanced or sustained by a binary companion that spins up the PPN.

In all of these cases, a binary companion is either required or helps to enhance the mechanism to produce the bipolar lobes. Thus it is increasingly common to hear it stated that bipolar PPNe and PNe are due to the effect of a binary companion, or even that the presence of a bipolar structure implies a binary. In this talk, I will review the evidence to support this claim for PPNe.

## 2 Ways to Detect a Binary Companion in a PPN

### 2.1 Visible Companion

Visible companions will necessarily be far from the PPN central star, given the typically large distance to PPN (1 to several kpc). A PPNe 1 kpc away with a companion in a circular orbit separated by  $0.5''$  from the PPN central star would have a semi-major axis of  $a = 500$  AU and a period  $P \approx 10^4$  yr (for  $M_{PPN} + M_{comp} = 1.0 M_{Sun}$ ). Evidence for a visible companion can be sought from high-resolution images of PPNe. The results from several such studies are listed below.

- Approximately 65 PPNe have been imaged in visible wavelengths by *HST* with  $R \sim 0.1''$  [22, 19, 16, 18], though however, none of these show a binary companion (0/65).
- Approximately 15 PPNe have been imaged in near-IR wavelengths by *HST* with  $R \sim 0.2''$  [20, 24, 16, 11], but none of these show a binary companion (0/15).
- Of 9 bipolar PPNe recently imaged at near-IR wavelengths with an adaptive-optics system on the Keck II 10-m telescope with  $R < 0.1''$  [17], 8 show no evidence of a companion and 1 shows indirect evidence of second source of light in the nebula (0–1/9).

These studies involve  $\sim 70$  different PPNe, yet none shows direct evidence of a visible companion. And, of course, the effect of a distant companion on the shaping of the PPN is greatly reduced. This method is useful for the detection of distant companions.

### 2.2 Photometric Variations

The interactions with a close binary companion can cause several types of detectable photometric variations. These would be particularly pronounced in PPN binaries with periods less than a few months. These are as follows:

- *Eclipses.* These are unlikely unless the companion is orbiting close to the photosphere of the PPN central star.
- *Re-radiation of light incident from the companion.* This is significant if the two stars are close together and of different temperatures; in this case, it would require a hot companion. The resulting light variation would have a period equal to the orbital period.

- *Ellipsoidal light variations.* Tidal distortions caused by a close companion produce a change in the shape and phase-dependent cross section of the PPN central star and thus in the brightness. The light variations would produce two maxima during one orbit, resulting in a photometric period equal to half of the orbital period.

These are the photometric methods used successfully by Bond [3] and more recently others [9] to detect binary companions to the central stars of PNe. These have resulted in the detection of binaries with periods of 1 to 16 days, and the conclusion that 10–15% of PNe have close binary companions. These photometric methods would allow the detection of close companions. We have carried out a long-term monitoring program of light variability in 24 PPNe, which resulted in the detection of variation in all cases. The results of this study will be referred to later.

### 2.3 Composite Spectra

Another way to detect a companion would be through a composite spectrum, either seeing the spectral lines of two different stars in the spectrum or by seeing the evidence of two stars of differing temperature in the spectral energy distribution (SED). Of course in a PPN, one needs to take account of the effect of the dust (cool and perhaps warm) on the spectral energy distribution. A binary companion to one PPN, AFGL 4106, has been detected in this way [15] and has subsequently been confirmed by near-IR imaging [2]. This method would allow the detection of unresolved companions.

### 2.4 Radial Velocity Variations

A binary companion can produce a measurable periodic radial velocity variation in the PPN due to the orbital motion. This method is currently being used to search for binaries in PNe [6]. It can be used to detect companions at intermediate separations. For example, for a circular orbit with  $M_{PPN} = 0.6 M_{Sun}$ ,  $M_{comp} = 0.6 M_{Sun}$ , and a detection limit of  $10 \text{ km s}^{-1}$ , then at an orbital inclination of  $i = 90^\circ$ , a binary with  $P \leq 4 \text{ yr}$  can be detected, while if  $i = 30^\circ$ , a binary with  $P \leq 0.5 \text{ yr}$  can be detected. If the detection limit is  $3 \text{ km s}^{-1}$ , then these values increase to  $\sim 150 \text{ yr}$  and  $\sim 20 \text{ yr}$ , respectively. If instead  $M_{comp} = 0.2 M_{Sun}$  with  $3 \text{ km s}^{-1}$ , these values change to  $\sim 12 \text{ yr}$  and  $\sim 1.5 \text{ yr}$ , respectively. It is the results of such a survey of PPNe that we will discuss.

## 3 Our Radial Velocity Study of PPNe

### 3.1 Our Program

Observations were carried out at the Dominion Astrophysical Observatory, Victoria, Canada, with the 1.2-m reflector. The radial velocity spectrometer was used, which employs a mechanical mask containing  $\sim 300$  absorption lines. (This is the device used by McClure to detect the binary nature of the Barium stars [12].) These observations were carried out regularly over 3 seasons, with a few occasional observations gathered over 2 more.

Our targets were bright PPNe ( $V=7-11$  mag) with F–G supergiant spectra. These spectral types have the advantage of containing many sharp lines, in contrast, for example, to the spectra of PN central stars. Our typical precision was  $0.65 \text{ km s}^{-1}$ . Seven PPNe were observed, each 30 to 60 times over 1600 day. The data were searched for periodicity using the CLEAN algorithm. These same targets were also included in our photometric monitoring program, which began during the last year of the radial velocity study.

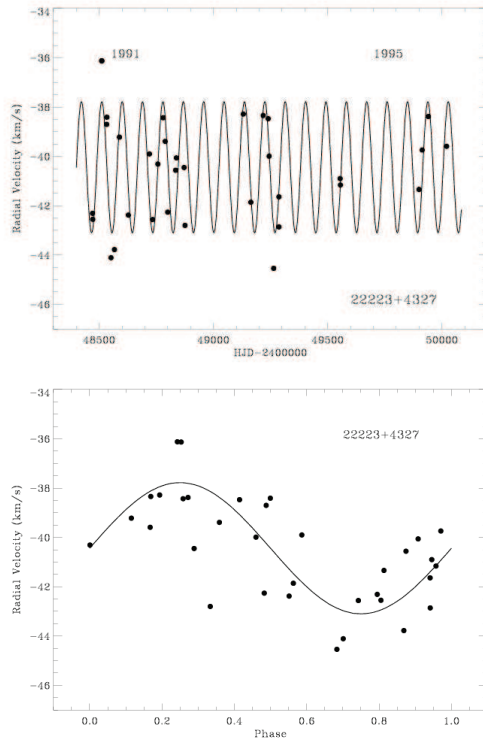
### 3.2 Results of the Radial Velocity Study

All 7 of the PPNe showed radial velocity variations, with a maximum range, peak-to-peak, of  $11 \text{ km s}^{-1}$ . Five of these appeared to vary periodically, with the other two possibly periodic as well. The individual results are as follows:

- *IRAS 22223+4327*. This object shows a radial velocity period of  $P(V_r) = 89$  days, similar to the light curve period of  $P(\text{LC}) = 90$  days. The velocity semi-amplitude is  $K = 2.7 \text{ km s}^{-1}$  assuming a sine curve. The individual velocities versus time are shown in Fig. 1a, and the phased velocity curve is shown in Fig. 1b. While the variation appears to be periodic, it does vary in amplitude.
- *IRAS 18095+2704*. These velocities show  $P(V_r) = 110$  days, similar to  $P(\text{LC}) = 113$  days, with  $K = 2.3 \text{ km s}^{-1}$ . The velocity curve is shown in Fig. 2a.
- *IRAS 22272+5435 (HD 235858)*. These velocities show  $P(V_r) = 125$  days, similar to  $P(\text{LC}) = 130$  days, with  $K = 1.6 \text{ km s}^{-1}$ . The velocity curve is shown in Fig. 2b.
- *IRAS 19500–1709 (HD 187885)*. These velocities show  $P(V_r) = 38.5$  days, with  $K = 2.8 \text{ km s}^{-1}$ . The light curves study reveals a change over time from a dominant period of 38 days to one of 41 days. The velocity curve is shown in Fig. 3a.
- *IRAS 17436+5003 (HD 161796)*. This object has a previous radial velocity study [5]. Combining our observations with these, we find  $P(V_r) = 53.5$  days and with  $K = 1.6 \text{ km s}^{-1}$ . The light curve is known to change, and from our data we find  $P(\text{LC}) = 44$  days. The velocity curve is shown in Fig. 3b.
- *IRAS 07134+1005 (HD 56126) and IRAS 19475+3119*. The radial velocity analyses for these two result in less well-determined periods. However, in each case, the most likely values of  $P(V_r)$  are on the order of  $P(\text{LC})$ .

For those with well-determined periods, the period from the radial velocity curve,  $P(V_r)$ , is approximately equal to the period determined from the light curves,  $P(\text{LC})$ ; this rules out a binary ellipsoidal light variation as the cause. Although  $P(V_r) \approx P(\text{LC})$ , the fact that the amplitudes of the velocity and the light curves vary from cycle to cycle rules out the binary re-radiation effect as the cause. **Thus we conclude that the radial velocity (and the light) variations are due to pulsation of the PPNe central stars and do not show evidence of a binary companion.** The results of this study are summarized in Table 1. The presence of pulsation complicates the search for binary companions, and in this study an upper limit for any binary motion can conservatively set at  $K < 2.5 \text{ km s}^{-1}$ .

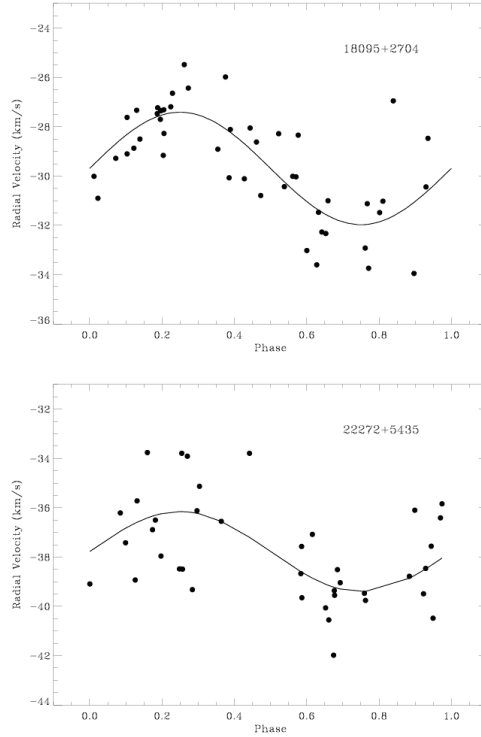
It should be noted that a pulsating central star does not in itself rule out the ability to determine the presence of a binary companion. 89 Her is known to be a pulsator with a binary companion with  $P(V_r) = 289$  days [1, 25]. From our data alone, we find  $P(V_r) = 292$  days, with  $K = 3.3 \text{ km s}^{-1}$  and an eccentricity of 0.18.



**Fig. 1.** IRAS 22223+4327 – (a) Left:  $V_r$  versus time; (b) Right: phased radial velocity curve (from [11]).

With the binary orbit removed, we find from our data  $P(V_r) = 66$  days, very close to the value we determine from our light curve data of  $P(LC) = 65$  days. Thus we were able to determine both periods.

One might question these results in light of the discovery of a number of post-AGB binaries by Van Winckel and collaborators [26]. But they are a distinctly different set of objects than these PPNe. They show a broad IR-excess (broad SED), indicating both hot and cool dust, and have abundance anomalies thought to be due to chemical fractionation of refractory elements onto dust, with re-accretion of non-refractory elements by the star. These properties are attributed to the presence of a circumbinary disk. Most and perhaps all of these objects are binaries, with  $P \approx 100\text{--}2600$  days, and the binary is thought to be responsible for forming and stabilizing the disk [27]. Thus it appears that it is their binary nature that leads to their special properties. They are likely low-mass objects that will *not* evolve into PNe. PPNe do not share these properties, but rather display a clearly double-peaked SED with only cool dust and with abundances in agreement with AGB evolution.



**Fig. 2.** Phased radial velocity curves of (a) IRAS 18095+2704 (left) and (b) IRAS 22272+5435 (right) (from [11]).

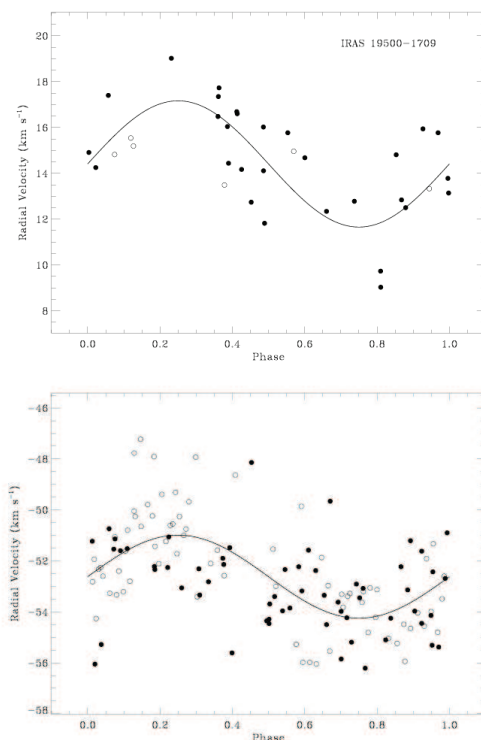
## 4 Conclusions

### 4.1 Why Were No Binaries Found in our Sample? A Selection Effect?

No binaries were found in our sample of 7 PPNe studied for radial velocity variation, although all of them varied due to pulsation. Might this lack of binarity be due to a selection effect? In particular, since the PPNe observed were the brighter ones with less obscuration, might one be simply looking nearly pole-on to the orbital plane and its associated obscuring torus?

We do know something about the orientation of the bipolar structure in these 7 PPNe based on HST images and on 2-D modelling in several cases with resolved mid-IR images. HST images of IRAS 18095+2704 and 19475+3119 suggest that they are viewed at some intermediate angle [22, 16]. Models have determined the following approximate inclinations of the polar axis with respect to the plane of the sky: IRAS 07134+1005,  $i \sim 80^\circ$  [14]; IRAS 17436+5003,  $i \sim 10^\circ$  [13, 8]; IRAS 22272+5435,  $i \sim 25^\circ$  [23].

Detection limits can be determined based on the binary pulsator 89 Her. Given its value of  $K = 3.3 \text{ km s}^{-1}$  and assuming that  $M_1 = 0.6 M_{Sun}$ ,  $M_{comp} = 0.35 M_{Sun}$



**Fig. 3.** Phased radial velocity curves of (a) IRAS 19500–1709 (left) and (b) IRAS 17436+5003 (right) (from [11]).

[4], then if  $P = 300$  days, we could detect the binary if  $i > 11^\circ$ , if  $P = 3$  yr, we could detect the binary if  $i > 18^\circ$ , and if  $P = 30$  yr, we could detect the binary if  $i > 39^\circ$ . Thus it does not seem likely that this null result is due solely to a selection effect based on orbital inclination.

#### 4.2 Implications of our Non-Detection of Binary PPNe

Let us begin with a comparison to the results of studies of binarity in PNe. It is found that at least 10–15% are photometric binaries. With their short periods, it seems likely that they formed through common envelope evolution. Radial velocity studies to investigate longer-period PNe binaries have revealed that many (most?) are variable [6]. However, that in itself does not mean that the variability is due to binarity; it could be due to pulsation. A recent volume-limited study of PNe concluded that  $\sim 50\%$  were binaries [7].

Might the PPNe be binaries, but presently in the common envelope stage? Since this stage is calculated to be very short, on the order of the orbital period [21], this cannot be the case. Might they be binaries but with periods longer than 30 yr? These would likely not be detected, but then their effect on shaping would be greatly

reduced. The above limits have been derived assuming main sequence or white dwarf companions. If the companion is a brown dwarf or a planet, then it would escape detection in our program.

Since in these 7 PPNe it is apparent that shaping of the nebula has started, these results might suggest two ways to form the shapes seen in PNe: (a) through common envelope evolution, as evidenced by the close binary nuclei of some PNe, or (b) through a non-common envelope process, which is occurring in these PPNe. This latter process might involve a distant and/or low-mass companion or be due to a single, pulsating PPNe.

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**Table 1.** Summary of Results of Our Radial Velocity Program of PPNe

IRAS	V (mag)	SpT	$\Delta V_r$ (km s <sup>-1</sup> )	P( $V_r$ ) (day)	P(LC) (day)	Results
07134+1005	8.2	F5 I	10	40	35	Pulsation
17436+5003	7.1	F3 Ib	8	53.5	44	Pulsation
18095+2704	10.4	F3 Ib	8	110	113	Pulsation
19475+3119	9.4	F3 I	10	47,39:	37,41	Pulsation
19500-1709	8.7	F3 I	11	38.5	38,41	Pulsation
22223+4327	9.7	G0 Ia	8	89	90	Pulsation
22272+5435	9.1	G5 Ia	8	125	130	Pulsation

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