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Where are the binaries in proto-planetary nebulae? Results of a long-term radial velocity study

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Abstract. We present the results of a long-term search (25 yrs) for radial velocity variability in a sample of seven bright proto-planetary nebulae showing axial symmetry. They all vary in velocity due to periodic pulsations. However, only marginal evidence is found for multi-year variations that might be due to a binary companion.

Keywords. binaries: spectroscopic − planetary nebulae: general − stars: AGB and post-AGB

1. Introduction

One of the outstanding problems in the study of planetary nebulae (PNe) concerns their shapes. While their AGB progenitors are basically spherical, PNe display a wide array of shapes, often axial or point-symmetric. Several mechanisms have been suggested to produce this morphology. These include the collimation of a fast wind by a torus produced by either (i) mass focused onto an orbital plan by a binary or (ii) mass lost preferentially in an equatorial plane by a rapidly rotating star. Another suggestion is (iii) a toroidal magnetic field that shapes the outflow of charged particles. While the first requires a binary explicitly, it is found in practice that the other two also require a binary to sustain them. Binaries companions to the central stars of PNe have been found in ∼15% of well-studied cases, primarily by photometric variability. Almost all have have short periods, less than a few days, and are assumed to be the result of common envelope evolution (see contributions by Nordhaus and by De Marco, this volume). A recent study demonstrated a tight correlation between the inclination of the binary and the inclination of the nebula (Hillwig *et al.* 2016). Periods longer than a few days are harder to find photometrically and fall into the realm of spectroscopic searches. See the review by De Marco (2009) of the evidence and role of binary central stars of PNe.

In this study, we have chosen to focus on a radial velocity search for binaries in proto-PNe (or pre-PNe; PPNe), the immediate precursors of PNe. They are distinguished by a large mid-IR excess due to cool dust from a detached circumstellar shell ("shell" sources). PPNe have the advantage of possessing F−G central stars, with more and narrower lines as compared to PNe. This allows the determination of more precise velocities. However,

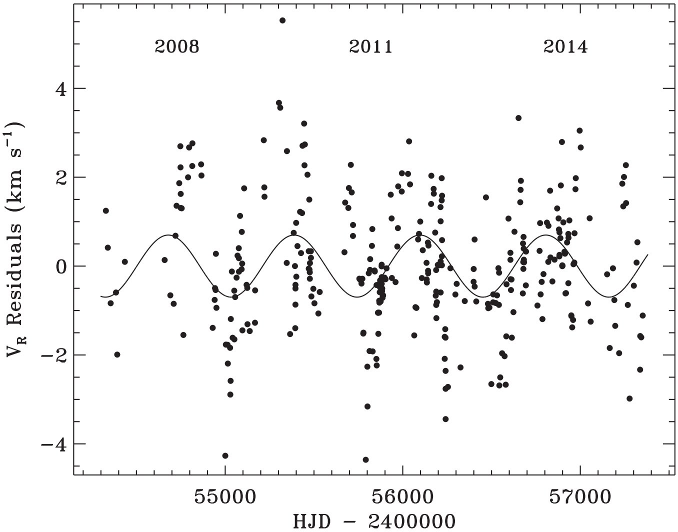

Figure 1. The observations of IRAS 22272+5435 following the removal of the periodic pulsations, fitted by a sine curve with P=710 days.

PPNe are known to vary due to pulsation, with periods in the range of 35−160 days (Hrivnak *et al.* 2010, Arkhipova *et al.* 2010), and this must be taken into account when searching for binary periods. These PPNe are to be distinguished from post-AGB F−G stars with near-IR excesses, all of which appear to be binaries (P∼120−1500 days) with circumbinary disks ("disc" sources; Van Winckel *et al.* 2009).

2. Observational Program

We have been carrying out a long-term observational study of the seven brightest (V<11) PPNe easily observable from the northern hemisphere using a 1−2 m telescope (Hrivnak *et al.* (2011)). They have been imaged in the visible (*HST*) and mid-IR and have bipolar or ellipsoidal shapes with sizes of a few arcsecs.

High-resolution spectroscopic observations were carried out with several telescopes and spectrographs over two different intervals of time. The initial observations were made in 1991−1995 at the Dominion Astrophysical Observatory (DAO) using a mechanical radial velocity spectrometer (RVS) attached to the 1.2m telescope. They revealed variations of ∼10 km s^{-1}, and in some cases periodic pulsation could be seen. Observations were re-initiated at the DAO in 2007, this time using a CCD detector. The program was enlarged to include observations made with the HERMES spectrograph (Raskin *et al.* 2011) on the 1.2-m Mercator Telescope in La Palma in 2009 and, for three of the objects, with a CORAVEL spectrometer on the 1.65-m telescope at the Moletai Observatory in Lithuania from 2008−2014.

3. Results

Multi-year studies. Pulsational variability was seen in all of the objects. In most of them, a clear periodicity could be seen with a timescale similar to what was found in their light curves (35−135 days). A search for longer, multi-year periodicity was unsuccessful in five of the objects, but some evidence was seen in two of them. It was revealed by variations in the mean seasonal velocities. For IRAS 22272+5435, the combined 2007−2015

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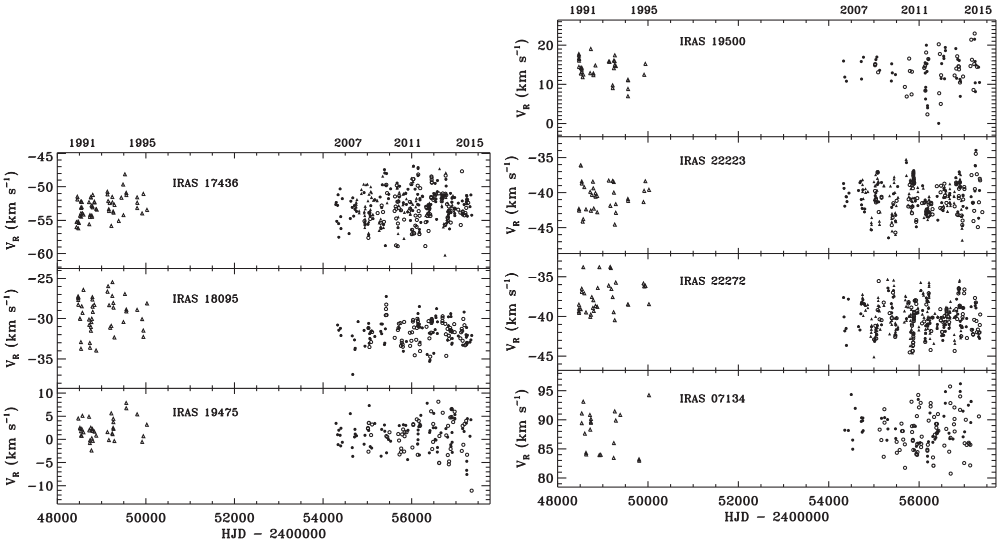

Figure 2. Comparison of the early (1991−1995) and recent (2007−2015) radial velocities.

data possessed a period of 710 days that just met our significance criteria (S/N=4.0 in frequency spectrum). Similarly, for IRAS 22223+4327, the 2009−2015 data suggested P≈770 days, but at a level just below our significance threshold. Searching the individual data sets supported periodic variability of this order in some cases but not in others. In neither of these cases is the result strong evidence for this longer, P∼ 2 year, period. In Figure 1 is shown for IRAS 22272+5435 a sine curve fit to the residuals of the radial velocities following the removal of the pulsational variations. While it fits the general trends in the data, the scatter is still large (σ∼1.3 km s^{-1}). Much of this, however, is due to the irregular nature of the pulsations, which can be seen in the varying amplitudes of the light and velocity curves.

Multi-decadal studies. The large total range of 25 years in the data of the two epochs (1991−1995 and 2007−2015) provides an opportunity to investigate even longer periodicities. However, this is complicated by inhomogeneities in the different radial velocity data sets. Comparison of velocities from the three sites showed systematic offsets in the data observed over the same time periods (2008−2015), even though they are each tied to IAU standard radial velocity stars. These offset values range from −1.1 to as large as +2.5 km s^{-1} in one case, with respect to the HERMES data, and these empirically-determined values were applied when combining the data sets. We attribute these systematic differences to several causes that manifest themselves in the measurements of the velocities of these complex spectra. These include the different spectral regions and ranges observed and different methods of fitting the profiles.

With these complications in mind, we compared the average values of the early DAO-RVS velocities (1991−1995) to the more recent data (2007−2015) adjusted to the HERMES values. These are shown in Figure 2. Differences between the two epochs were within the above offset values found among the different data sets (<± 2.0 km s^{-1}) except for two objects. For IRAS 18095+2704, the difference is 2.2 km s^{-1} and for IRAS 22272+5435, it is 3.0 km s^{-1}. These might suggest a long-term, multi-decade radial velocity variation, particularly in IRAS 22272+5435, but confirmation will require continued observations of the object with the same or similar instruments.

4. Discussion and Conclusions

Results thus far. The radial velocities of a sample of bright PPNe have been examined over several timescales, and several results have been found thus far.
1. Pulsation periods of 35−135 days have been found for each of them.
2. Evidence for multi-year periodic variations is weak, with only two of the objects showing suggestions of this (P≈2 yrs) at a level just at or below the significance criteria. And in these two cases, the results were seen in only some of the data sets.
3. Evidence for multi-decade variations is seen in two of the objects, being strongest in IRAS 22272+5435. However, as discussed above, the interpretations of the difference between the early and later data sets is tempered by the discovery of systematic differences (offsets) between the three recent contemporaneous data sets. The larger, multi-decade variation observed in IRAS 22272+5435 might be real, but will require continued long-term observations with the same or a similar device to confirm.

In our initial study of these seven PPNe, we discussed the possibility that our targets are biased toward low inclination as a result of our choice to observe those with bright central stars (Hrivnak *et al.* 2011). However, published modeling of their envelopes based on mid-IR observations indicates this not to be the case in general, and limiting values of P and M_2 were determined for undetected companions.

Ways ahead for progress. Several ways suggest themselves to make progress on the radial velocity search for binaries in PPNe.
1. Continue to observe these PPNe with the same or a similar device to investigate the suggested 2-year periodicity and the decadal shift in velocities.
2. Improve our analysis with a better selection of lines to probe deeper in the star where the effects of pulsation are lessened.
3. Observe edge-on PPNe, where one would see the full impact of the velocity along the line of site. We have begun such a study of three edge-on PPNe for which the central star is obscured in visible light but seen in the near-infrared. Initial results are suggestive, but only a few spectra have been obtained thus far and they require 8-m class telescopes.

Where are the binary companions? We conclude with the question that we began with. Where are the binaries?
1. They are present but hidden in long-period (>15 year) orbits − perhaps.
2. They are present but hidden due to the low mass of the secondaries (<0.2 $M_\odot$), which might even be planets (see contribution by Villaver, this volume) − perhaps.
3. They are present but hidden inside the atmosphere of the F−G star − unlikely due to timescale arguments for spiraling in.
4. They are merged with the central star − but there is no evidence to support this. They appear as normal post-AGB stars and are not rapid rotators.
5. They are absent and these PPNe are evolving as single stars.
Thus the present observational evidence, based on precise radial velocity measurements of PPNe, does not provide direct support for binary companions. To prove or exclude the presence of binaries is crucial to our understanding of the way(s) that bipolar PPNe and PNe form.

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Discussion

Sloan: What dominates your error budget for radial velocity measurements in the optical spectra?

Hrivnak: The error budget is dominated by complex, variable line shapes due to pulsation. Also, S/N and aperture of telescopes available.

Q: Thanks for your extraordinary efforts over the years in collecting such as extraordinary set of observational data. I am particularly interested in the sources in you sample showing complex multi-polar morphologies. To me, this is very difficult to explain under the current assumption that these are formed by binary systems. Moreover, as they do not seem to display any particular photometric behaviour or signs of binarity in your data. Can you comment on this? Maybe a question to the experts on shaping of PNe ...?

Hrivnak: Thank you for your kind words of encouragement. One particular source, IRAS 19475+3119, is clearly multipolar. And I agree, such a morphology seems difficult to explained by a binary. Perhaps one could try to appeal to a model of a binary with a precessing disk (due to a 3rd star) and episodic mass out flows. But that is a question best addressed by the binary modelers.