PLANETARY NEBULAE: THEIR EVOLUTION AND ROLE IN THE UNIVERSE
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Proto-Planetary Nebulae

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Abstract. The study of proto-planetary nebulae (PPNs) leads to a better understanding of both the preceding asymptotic giant branch and the succeeding planetary nebula phases of stellar evolution. Recent results are reviewed, emphasizing the properties of the central stars and the shape and chemistry of the nebulae. The study of PPNs is seen to be important in its own right.

1. Introduction

Proto-planetary nebulae (PPNs) are the immediate precursors of planetary nebulae (PNs). They are objects in transition from the asymptotic giant branch (AGB) to the PN phase of stellar evolution. In this transitional phase, (extensive) mass loss has ended but photoionization has not yet started.

While the observational study of PNs goes back over 200 years, the study of PPNs is quite recent, less than 20 years old. The properties of PPNs are expected to lie between those of AGB stars and PNs. However, there are several properties of PPNs that have made their discovery difficult. They are in a short-lived stage of stellar evolution, only a few thousand years (Blöcker 1995), the central star is partially obscured by the circumstellar envelope (CSE), and they are not easily distinguished from normal stars in visible surveys. The discovery of such objects began in 1984, following from the IRAS all-sky infrared survey. The identification of PPN candidates has been based upon the infrared excess from the cool dust in the CSE.

2. Initial Follow-up Studies

Initial studies that followed up on these identifications were naturally made at low resolution. The central stars were found to possess spectral types from G to B, primarily F and G. Their luminosity classification was Iab, indicative of their low surface gravity. In some cases spectroscopic anomalies were seen, such as strong lines of s-process elements and of C_2 and C_3 (Hrivnak 1995). The CSEs were detected in millimeter-wave surveys in spectral lines of CO, OH, and HCN (Likkel 1989; Likkel et al. 1991; Omont et al. 1993) and revealed expansion velocities of 10−15 km s^{-1} and mass loss rates of 10^{-6} to as high as 10^{-4} $M_\odot$ yr^{-1}. The infrared emission from the dust in the CSE was observed with T_d=150−250 K. The spectral energy distributions for these objects showed a distinctive double-peaked appearance. An example is shown in Figure 1.

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At present, there are about 60 good PPN candidates known (Kwok 1993; García-Lario et al. 1997). It is not always easy to determine the exact nature of the candidates, and in some cases there may be, for example, confusion with massive, mass-losing supergiants. Detailed abundance analyses help in some cases. Note that PPNs should be distinguished from low-mass, post-AGB objects that will evolve at too slow a rate to become PNs and also from unusual binaries with circumbinary dust disks producing infrared excesses (Van Winckel 1999). In this review, we will update what we have learned about PPNs in the last several years, highlighting in particular the results of studies at higher resolution.

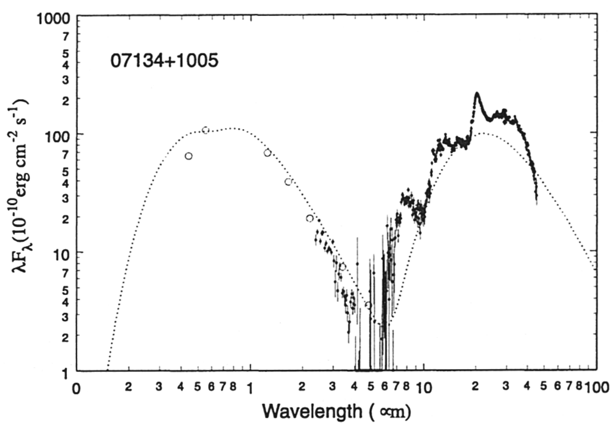

Figure 1. Double-peaked spectral energy distribution of the PPN IRAS 07134+1005. Approximately equal amounts of energy are detected from the reddened photosphere of the central star and from the circumstellar dust. Note the strong emission feature ~ 21 μm.

3. Central Star: (looking back to the AGB phase)

3.1. Detailed Abundances

High-resolution (R~15,000–60,000) visible spectroscopy has been carried out for about a dozen of the brighter PPNs. They can be divided into two groups based upon their carbon to oxygen ratios. For the carbon-rich PPNs, average abundance values of [Fe/H]=−0.7, [C/Fe]=+0.9, [s-process/Fe]=+1.5 have been found from the study of ten objects (Van Winckel & Reyniers 2000; Reddy, Baker, & Hrivnak 1999; Klochkova et al. 1999). These show clear evidence for nucleosynthesis and third dredge-up on the AGB. On the other hand, for the oxygen-rich PPNs, the values are [Fe/H]=−0.5, [C/Fe]=+0.4, [s-process/Fe]=0.0 based on studies of two bright objects. This leads to the question of why the oxygen-rich PPNs do not show the expected post-AGB abundance patterns of enhanced s-process elements. The results of detailed abundance studies of PPNs are discussed in more detail by Van Winckel (these proceedings).

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3.2. Variability

The light variability of HD 161796 (P=45 d) has been know for 40 years, prior to its identification as a PPN, and the variability of a few other individual objects has been recently cited. An extensive photometric monitoring program has been carried out for eight years at Valparaiso University, examining the light variation of $\sim$40 PPN candidates. It is found that the large majority of them display moderate-amplitude light variations, with $\Delta V=0.15-0.40$ mag. Quasi-periods have been found for ten objects of spectral types F and G, with values of $P\sim45-145$ d. Those with earlier spectral type (B) show shorter-term variability. Most of the variability is attributed to pulsation; this is supported by radial velocity studies showing variability. There is a general trend of shorter-term variability with hotter stars; this what would be expected in general since the hotter stars have smaller radii at constant luminosity (Hrivnak et al. 2001). The results of such studies can provide information on the structure of these stars and might also bear upon the question of post-AGB mass loss.

4. Circumstellar Envelope: (looking forward to the PN phase)

4.1. Nebular Shapes and Shaping

The shape of PPNs has from their discovery been an interesting question. Observations of AGB stars show that they possess spherical envelopes. On the other hand, PN display a range of shapes from elliptical to bipolar to point-symmetric. Do these PN shapes develop through gradual processes or are they imprinted early in the nebula? Imaging observations of PPNs can answer this question and help us to learn about the shaping process.

HST Imaging: High spatial-resolution observations with the Hubble Space Telescope (HST) were required to answer the question of the shape of the nebulae. The HST image of the Egg Nebula (Sahai et al. 1998a) is well known, and examples of four other PPNs are shown in Figure 2. PPNs are seen to display the range of shapes seen in PNs, even point symmetry (Kwok, Su, & Hrivnak 1999; Su et al. 1999; Hrivnak, Kwok, & Su 1999; Ueta et al. 2000, which contains a larger survey of $\sim$18 PPNs). These studies show that a bipolar shape is common in PPNs and suggest that perhaps they all have a basic bipolar structure. The differences in appearance then arise from the orientation of the nebula and both the density and asymmetry of the CSE (Su, Hrivnak, & Kwok 2001; Ueta et al. 2000, who divide their sample into two distinct classes based upon visible and mid-infrared morphology differences). Dense obscuring regions, perhaps including a torus, are seen separating the lobes in bipolar PPNs. Recently such a torus has been seen directly in scattered light, and it appears to be collimating the bipolar outflow (Kwok, Hrivnak, & Su 2000; see Fig. 2).

How this bipolar structure carries over to the PN stage, when one is no longer looking at scattered light but emission from the gas, is an interesting question that will not be explored here.

Circumstellar Arcs: The morphology of the PPNs implies that the transition from a spherical AGB envelope to a bipolar PPN must happen quickly. This

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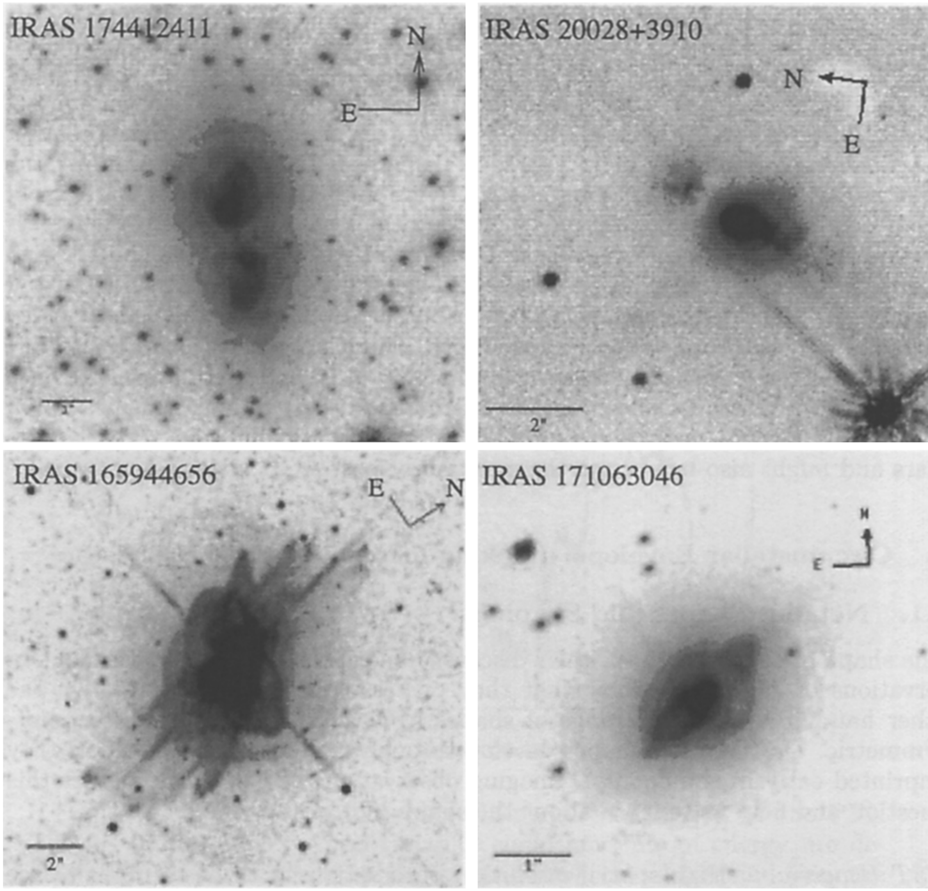

Figure 2. Examples of bipolar PPNs. Circumstellar arcs seen in several and an equatorial disk is seen in IRAS 17106−3046.

change in morphology has been preserved in the circumstellar arcs and rings observed thus far abound five PPNs, four PNs, and one AGB star (Hrivnak, Kwok, & Su 2001). Examples are shown in Figure 2.

Their detection in bipolar PPNs with differing orientations confirms that they are portions of illuminated shells. The numbers of arcs observed range from >20 in the Egg Nebula to three in IRAS 17441−2411. If they expand at the same rate as the molecular gas in the CSE, then their spacing implies a time scale of 10^2-10^3 yr. This time scale is longer than that for stellar pulsation ($\sim$1 yr) but shorter than that predicted for thermal pulses (10^4-10^5 yr). A variety of explanations have been suggested. These include the effects of a binary companion (Harpaz, Rappaport, & Soker 1997; Mastrodemos & Morris, 1999), periodic mass loss, magnetic cycles on a star (Soker 2000; García-Segura, López, & Franco 2001), and gas-dust hydrodynamics (Simis, Icke, & Dominik 2001).

At this point, it is not clear how common a phenomenon these arcs are. But it is striking to see the spherical shells and the bipolar lobes simultaneously. The mechanism that causes the lobes apparently involves a higher-speed outflow that does not disturb the overall spherical structure of the envelope.

Mid-Infrared Imaging: While imaging observations at visible and near-infrared wavelengths show the appearance of the nebula in scattered light, observations in the thermal mid-infrared allow one to see emission arising directly from the dust. A mid-infrared survey by Meixner et al. (1999) barely resolved PPNs with sizes of $1-2''$. More detail has been seen in a few larger ones, which display asymmetric dust distributions (Meixner et al. 1997; Dayal et al. 1998). Until just recently, these studies were limited by the size of the telescope aperture to a resolution of $\sim 0\farcs9$, near the diffraction limit of a 3–4 m telescope. Studies of PPNs are just beginning with the new, larger telescopes such as the MMT (Ueta et al. 2001), Keck (Jura, Chen, & Werner 2000), and especially the infrared-optimized Gemini Telescopes ($R \sim 0\farcs4$ at 10 μm; Kwok, Volk, & Hrivnak 2002).

Shaping of the Nebulae: On the basis of the high spatial-resolution images obtained over the past five years, it is established that PPNs commonly have a bipolar structure. Balick (1987) showed how elliptical and bipolar PNs could be produced by a stellar wind expanding into a medium with a density gradient. This then raises the question of what produces the density enhancement, even to the extent of producing a torus in some cases.

Various theoretical models have been proposed which change the stellar mass loss from being isotropic to having a preferred plane. These include the interaction with a binary companion (star or planet) that diverts mass loss into the orbital plane (Livio & Soker 1988), and rapid rotation, perhaps induced by an interacting binary companion, that leads to a preferred plane for mass loss (García-Segura et al. 1999, and references therein). The effect of magnetic fields on producing a bipolar outflow has also been considered (García-Segura et al. 1999).

Binary companions have frequently been invoked as a cause of the bipolar structure. However, direct observational evidence to support this claim is lacking. In cases in which there exists a visible companion or the central star is seen to be displaced from the center of the nebula, the possible companion is too far away from the central star to have caused the bipolarity. In a study that we carried out to search for radial velocity variability in nine of the brightest PPNs, no evidence for a close companion ($P \lesssim 2$ yr) was found (Hrivnak & Lu 2000).

If the shaping of the lobes is produced by a fast outflow from the central star, can one see evidence of this in the PPN phase? Yes, this has been seen in the extended wings of the submillimeter CO lines in a few PPNs, such as the Egg Nebula, AFGL 618, and IRAS 19500−1709. One can also see evidence of this fast outflow in H_2 emission. Kastner et al. (2001) observed spectral evidence of a fast, decelerating outflow along the lobes in the Egg Nebula and AFGL 618. H_2 imaging can locate the region where the fast outflow interacts with the AGB remnant.

In the Egg Nebula this is seen at the ends of the bipolar lobes and at the ends of the equatorial obscuring region (Sahai et al. 1998b). H_2 emission is also seen at the ends of the lobes for the bipolar PPN IRAS 17150−3224 (Fig.

3a). Examination of the strengths of the H_2 spectral lines (Fig. 3b) indicates that they are shock-excited by collisions. H_2 spectroscopic surveys have recently been carried out of ~50 PPN candidates (García-Hernandez et al. and Kelly & Hrivnak, these proceedings). When compared with the results of past studies of PNs, they appear to show an evolution in the H_2 emitting regions.

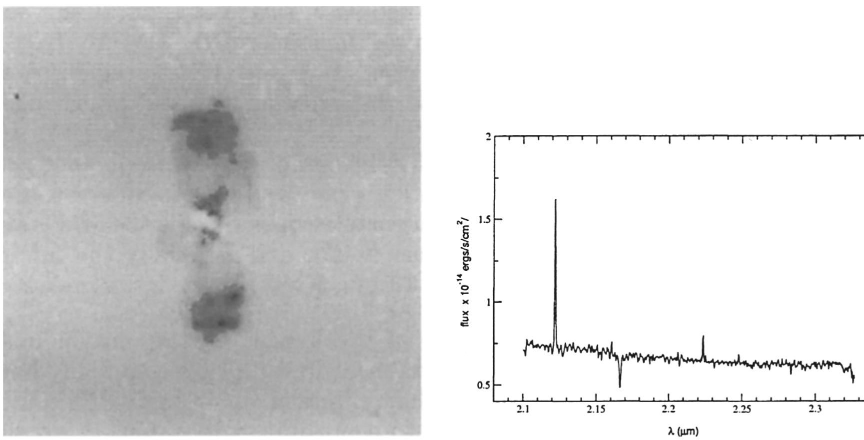

Figure 3. Left – H_2 image of IRAS 17150–3224; Right – 2 μm spectrum showing the H_2 emission line strengths.

4.2. Chemistry of the CSE

The infrared spectra of PPNs have shown some interesting surprises. A new emission feature at 20.1 μm ("21 μm feature"; see Fig. 1) has been seen in 12 PPNs (Kwok, Volk, & Hrivnak 1999; Volk, Kwok, & Hrivnak 1999), all of which are carbon-rich and show post-AGB abundance patterns (Van Winckel 1999). This feature is seen almost exclusively in PPNs. The 30 μm feature, previously seen in carbon-rich AGB stars and PNs, has also been seen in PPNs (Omont et al. 1995), and it has recently been resolved into a 26 μm feature and 33 μm feature with ISO spectra (Hrivnak, Volk, & Kwok 2000; Volk et al. 2002). This resolved 30 μm feature is seen in all of the sources that have the 21 μm features. These three features make a relatively large contribution to the total flux observed from these sources, 25–50%.

Identifications for these features are uncertain. Recent suggestions for the source of the 21 μm feature include nanodiamonds (Hill et al. 1998), TiC nanocrystals, which appear to produce a very good fit to the shape and wavelength of the feature (von Helden et al. 2000), and SiC (Speck et al., these proceedings). The TiC suggestion, which involves a less abundant element in Ti, appears to demand rather tight constraints on the formation process, requiring a very high mass-loss rate ~10^{-3} $M_\odot$ yr^{-1} over a short time period. This is not supported by our recent submillimeter observations of CO (4–3) and (2–1) transitions. The higher transition observation allows one to sample regions of the CSE closer to the central star, and they rule out the very high mass-loss rate or mass-loss jump suggested by the TiC model for the 21 μm feature.

This discussion has focused on the carbon-rich PPNs. Crystalline silicates are seen in some oxygen-rich PPNs (Waters & Molster 1999).

5. Summary, Questions, and a Look to the Future

We have seen that the study of PPNs is important as a link to the preceding AGB phase of stellar evolution. In particular, it provides an ideal setting to investigate the results of nucleosynthesis during the AGB phase. The expected CNO and s-process enhancements are seen in carbon-rich PPNs but not oxygen-rich ones. PPNs also serve as a link to the succeeding PN phase. In particular, they hold the key to the shaping of the nebulae. Bipolarity is found to be common and circumstellar shells may also be common. We see that the shaping from spherical to bipolar takes place quickly, although the exact mechanism is not yet certain. Present questions include the role of winds versus jets and the role of binaries versus magnetic fields.

In addition, the study of PPNs has become important in its own right. In particular, it provides an opportunity to study the chemistry of the nebula in a changing radiation and density environment. New features, like the 21 μm emission feature, have spurred new laboratory studies.

Future studies in PPNs, as in other areas of stellar astrophysics, will continue to push toward higher resolution. With the larger infrared telescopes, we will be able to use mid-infrared imaging to map the distribution of the dust directly and to locate the sources of the various emission features. With the future submillimeter arrays like ALMA, we can expect to get detailed maps of the radial and azimuthal distributions of molecules in the CSEs. The study of PPNs in local group galaxies, in which they will be at known distances but in different metallicity environments, will be made possible by SIRTF. New orbiting telescopes are planned that will allow us to get trigonometric parallaxes for PPNs in our own galaxy. These prospects for the near future will lead to deeper insights into the evolution and mass loss processes in these evolved phases.

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References

Balick, B. 1987, AJ, 94, 671
Blöcker, T. 1995, A&A, 299, 755
Dayal, A., et al. 1998, ApJ, 492, 603
García-Lario, P., et al. 1997, A&AS, 126, 479
García-Segura, G., Langer, N., Różycka, M., & Franco, J. 1999, ApJ, 517, 767
García-Segura, G., López, J.A., & Franco, J. 2001, ApJ, 560, 928
Harpaz, A., Rappaport, S., & Soker, N. 1997, ApJ, 487, 809
Hill, H.G.M., Jones, A.P., & d'Hendecourt, L.B. 1998, A&A, 336, L41

Hrivnak, B.J. 1995, ApJ, 438, 341
Hrivnak, B.J., Kwok, S., & Su, K.Y.L. 1999, ApJ, 524, 849
Hrivnak, B.J., Kwok, S., & Su, K.Y.L. 2001, AJ, 121, 2775
Hrivnak, B.J., Kwok, S., & Volk, K.M. 1989, ApJ, 346, 265
Hrivnak, B.J., & Lu, W. 2000, in IAU Symp 177, The Carbon Star Phenomenon, ed. R.F. Wing (Dordrecht: Kluwer), 293
Hrivnak, B.J., et al. 2001, in Post-AGB Objects as a Phase of Stellar Evolution, eds. R. Szczerba & S.K. Gorny (Dordrecht: Kluwer), 101
Hrivnak, B.J., Volk, K., & Kwok, S. 2000, ApJ, 535, 275
Jura, M., Chen, C., & Werner, M.W. 2000, ApJ, 544, L141
Kastner, J.H., Weintraub, D.A., Gatley, I., & Henn, L. 2001, ApJ, 546, 279
Klochkova, V.G., Szczerba, R., Panchuk, V.E., & Volk, K. 1999, A&A, 345, 905
Kwok, S. 1993, ARA&A, 31, 63
Kwok, S., Hrivnak, B.J., & Su, K.Y.L. 2000, ApJ, 544, L149
Kwok, S., Su, K.Y.L., & Hrivnak, B.J. 1999, ApJ, 501, L117
Kwok, S., Volk, K., & Hrivnak, B.J. 1999, in IAU Symp 191, Asymptotic Giant Branch Stars, ed. T. LeBertre, A. Lebre, & C. Waelkens (San Francisco; ASP), 297
Kwok, S., Volk, K., & Hrivnak, B.J. 2002, ApJ, 573, 720
Likkel, L. 1989, ApJ, 344, 350
Likkel, L., Forveille, T., Omont, A., & Morris, M. 1991, A&A, 246, 153
Livio, M., & Soker, N. 1988, ApJ, 329, 764
Mastrodemos, N., & Morris, M. 1999, ApJ, 523, 357
Meixner, M., et al. 1997, ApJ, 482, 897
Meixner, M., et al. 1999, ApJS, 122, 221
Omont, A., et al. 1993, A&A, 267, 607
Omont, A., et al. 1995, ApJ, 454, 819
Reddy, B.E., Baker, E.J., & Hrivnak, B.J. 1999, ApJ, 524, 831
Sahai, R., et al. 1998b, ApJ, 492, L163
Sahai, R., et al. 1998a, ApJ, 493, 301
Simis, Y., Icke, V., & Dominik, C. 2001, A&A, 371, 205
Soker, N. 2000, ApJ, 540, 436
Su, K.Y.L., Hrivnak, B.J., & Kwok, S. 2001, AJ, 122, 1525
Su, K.Y.L., Volk, K., Kwok, S., & Hrivnak, B.J., 1999, ApJ, 508, 744
Ueta. T., Meixner, M., & Bobrowsky, M. 2000, ApJ, 528, 861
Ueta. T., et al. 2001, ApJ, 557, 831
Van Winckel, H. 1999, in IAU Symp 191, Asymptotic Giant Branch Stars, ed. T. LeBertre, A. Lebre, & C. Waelkens (San Francisco; ASP), 465
Van Winckel, H., & Reyniers, M. 2000, A&A, 354, 135
Volk, K., Kwok, S., & Hrivnak, B.J. 1999, ApJ, 516, L99
Volk, K., Kwok, S., Hrivnak, B.J., & Szczerba, R. 2002, ApJ, 567, 412
von Helden, G., et al. 2000, Sci., 288, 313
Waters, L.B.F.M., & Molster, F.J. 1999, in IAU Symp 191, Asymptotic Giant Branch Stars, ed. T. LeBertre, A. Lebre, & C. Waelkens (San Francisco; ASP), 209