PROTO-PLANETARY NEBULAE

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Abstract.

We review the properties of proto-planetary nebulae, highlighting the advances in our quantitative knowledge of these objects. The discussion focuses on the chemistry and morphology of their circumstellar envelopes and the chemistry and variability of their central stars.

1. Introduction

In this presentation, we will review our current knowledge of proto-planetary nebulae (PPNe), objects in transition between the asymptotic giant branch (AGB) and planetary nebula (PN) phases. A PPN consists of a central star evolving to the left on the HR diagram, surrounded by a detached, expanding circumstellar envelope (CSE) of gas and dust. Observations reveal a "double-peaked" spectral energy distribution (SED), composed of light from a reddened photosphere and re-emission from circumstellar dust (see Hrivnak, Kwok, & Volk 1989). There has been much research in this field since the last PN conference (Kwok 1993a,b), and we will attempt to highlight this. Some has continued to be of a quantitative nature, with the identification and classification of new PPNe, but an increasing amount has been of a quantitative nature, with regard to both the CSE and the central star.

Observationally, the coolest PPN stars appear to have a spectral type of late-G, or a temperature $\sim 5000\,\mathrm{K}$ (Hrivnak 1995). Photoionization occurs when the temperature of the central star reaches $\sim 30,000\,\mathrm{K}$, and we will regard this as the beginning of the PN stage. This sets the approximate temperature and spectral ranges expected for PPNe. Theoretical studies show that the transition times scale for the PPN phase, from the time when extreme mass loss on the AGB has ended (and the remaining envelope

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mass is $< 10^{-3}\,M_\odot$) and photoionization begins, is small, $\sim 10^3$ yrs (Blöcker 1995).

2. Circumstellar Envelopes: Chemistry

2.1. MOLECULAR-LINE STUDIES

PPN candidates have continued to be observed in OH, CO, and HCN. From these, Omont *et al.* (1993) determined criteria to allow one to classify the chemistry (C or O) of the objects on the basis of the ratio of CO/HCN: for C-rich sources, CO(1-0)/HCN < 5 or CO(2-1)/HCN < 12. Additional molecules have also been detected.

2.2. VISIBLE SPECTROSCOPY

Hrivnak (1995) identified molecular C_2 and C_3 absorption features in 8 PPN candidates, in addition to the Egg nebula, a previously known source. These are found in G and even some F stars, where the temperature is too high for them to be photospheric.

With observations at higher resolution, Bakker *et al.* (1996, 1997; also Reddy *et al.* 1996) have made a detailed study of molecular absorption features in all 9 of these PPNe, plus some additional post-AGB stars. They identified the vibrational bands of C_2 and CN in all nine. (These will be listed later in Table 1). From these, they were able to determine expansion velocities for the molecules of 5–44 km s^{-1}, values which agree very well with the CO millimeter-line expansion velocities, and rotational temperatures of 43–399 K for C_2 and 18–50 K for CN. This clearly identifies the CSE as the location of these molecules. Column densities for the molecules were determined and mass loss rates estimated. Thus the application of high-resolution optical spectroscopy provides a new and useful probe of the chemical and physical properties of the CSEs in PPNe, at least in C-rich ones.

2.3. NEAR-INFRARED SPECTROSCOPY

Near-infrared spectra have been obtained of a number of PPNe (Hrivnak, Kwok, & Geballe 1994; Oudmaijer *et al.* 1995). A few are found to show CO in emission at 2.3 μm, and for IRAS 22272+5435, the CO varied from emission to absorption over a 3 month period. Emission at 3.3 and 3.4 μm, commonly attributed to polycyclic aromatic hydrocarbons (PAHs), is seen in several carbon-rich PPNe. In a few of these, the 3.4 μm feature is unusually strong compared with the usually dominant 3.3 μm feature (Geballe *et al.* 1992).

2.4. MID-INFRARED SPECTROSCOPY

IRAS: The IRAS LRS spectra provided an opportunity to classify the chemistry of the CSEs of evolved stars on the basis of the presence of silicate features at 9.8 and 18 μm or silicon-carbide features at 11.3 μm. Indeed, the 9.8 and 18 μm features have been seen in emission in several PPN candidates. While the silicon-carbide feature has not been seen, several other features have been identified which are indicative of a C-rich CSE.

PAHs: Strong UIR features at 6.2, 7.7, 8.6, 11.3 μm, attributed to PAHs, have been seen in several C-rich, typically young PNe. In PPNe, the feature at 7.7 μm appears to be at the edge of the IRAS LRS spectra in several PPNe. By using KAO, Buss *et al.* (1990) identified strong infrared emission features at 6.9, 8, and 12 μm. In these cool objects, it is suggested that visible photons pump the PAH bands. Recently, using mid-infrared spectra obtained with the UKIRT CGS3 spectrometer, Justtanont *et al.* (1996) observed several carbon-rich PPNe and found in addition to the standard UIR features new features at 7.9, 8.2, 10.6, 11.5, and 12.2 μm, which they attribute to the PAH molecule chrysene.

21 μm: The "21 μm" emission feature was first identified by Kwok, Volk, & Hrivnak (1989) in the IRAS LRS spectra of 4 PPNe.Associated with it is a flat "plateau" in the spectrum from 12–18 μm, emission from 11–12 μm, and perhaps an emission feature at $\sim 8\,\mu$m. Several additional sources have since been identified from the LRS database (Hrivnak & Kwok 1991) or from ground-based spectroscopy using the UKIRT CGS3 spectrometer (Kwok, Hrivnak, & Geballe 1995; Justtanont *et al.* 1996). This bring the number of 21 μm sources to 11.

The feature continues to be found only in PPNe (but see Henning, Chan, & Assendorp 1996, who recently claim to find it in several YSOs), and only in those which are clearly C-rich. The fact that it is seen only in PPNe indicates that it has a transitory or frail nature. It is not seen in the AGB stars, where it is either not present or present but not excited. In the PNe, it is not seen, presumably because it is destroyed by the uv radiation field.

In Table 1, we list the 21 μm sources and some of the particular properties common to most of them. The strong correlation with carbon and PAH features is evident, and most also have strong HCN measurements. In fact, on this basis, we predict two new 21 μm sources, which we plan to confirm with ISO. Suggestions continue to be made for the identification of the 21 μm feature (see Justtanont *et al.* 1996).

30 μm: A very broad feature at 30 μm is known from KAO observations to exist in the spectra of a range of C-rich evolved stars, from AGB stars to PNe (Cox 1993). This feature has been seen in the spectra of at least 5 PPNe, including the Egg nebula (Omont *et al.* 1995). This is a strong fea-

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TABLE 1. List of 21 μm sources and their common properties

ID	21 μm	30 μm	SpT	Optical	IR features (PAH)
04296+3429	strong	...	G0 Ia	C_2, C_3, CN	3.3, 3.4–3.5, 7.7, 11.3
05113+1347	medium	...	G7 Ia	C_2, C_3, CN	3.3, 11.3
05341+0852	weak	...	F6 I	C_2, C_3, CN	3.3, 3.4–3.5, 7.7, 11.3
07134+1005	v. strong	strong	F5 I	C_2, CN	3.3, 6.9
19500−1709	v. weak	...	F3 I	...	...
20000+3239	weak	v. strong	G7 Ia	C_2, CN	7.7, 11.3
AFGL 2688	weak	medium	F5 Iae	C_2, C_3, CN	3.3, 3.4–3.5
22223+4327	medium	...	G0 Ia	C_2, C_3, CN	...
22272+5435	strong	v. strong	G5 Ia	C_2, C_3, CN	3.3,3.4–3.5, 6.9, 7.7, 11.3
22574+6609	medium	...	...	...	7.7, 11.3
23304+6147	strong	v. strong	G2 Ia	C_3, CN	7.7, 11.3
"Predicted New Sources"					
02229+6208	not obs.	...	late-G I	C_2, C_3	...
07430+1115	not obs.	...	mid-G I	C_2, C_3	3.3, 3.4, 11.3

References: (1) Kwok, Volk, & Hrivnak 1989; (2) Hrivnak & Kwok 1991; (3) Buss *et al.* 1993; (4) Justtanont 1996; (5) Omont *et al.* 1995; (6) Hrivnak 1995; (7) Geballe *et al.* 1992; (8) Buss *et al.* 1990.

ture in some PPNe; in IRAS 22272+5435 it makes up 20% of the bolometric luminosity. All 5 of these PPNe also possess the 21 μm feature; however, the strength of the two features is not correlated. The best identification thus far for the origin of this 30 μm feature is MgS (Goebel 1980; Goebel & Moseley 1985), or a mixture of MgS and amorphous carbon grains (Omont *et al.* 1995), or a mixture of MgS and FeS (10%) (Szczerba *et al.* 1996).

We can eagerly look forward to the good ISO data to extend our knowledge of the prevalence of the 21 and 30 μm features, and to allow us to investigate substructure in these features and other new features. This will be exciting, and undoubtedly there will be much to learn here.

3. Circumstellar Envelopes: Morphology

3.1. INTRODUCTION

The ability to resolve images of PPNe can allow one to study the processes that go into shaping the PN nebulae. While the CSEs of AGB stars are generally spherically symmetric, although perhaps clumpy, the nebulae of most PNe display axial (not spherical) symmetry. This PN morphology is thought to arise from the interaction between the fast wind of the central star and the remnant CSE of the AGB progenitor. The axial symmetry thus requires a density enhancement in the plane perpendicular to the axis

(Balick 1987). Detailed hydrodynamic models confirm that this will produce the appearance of the observe PNe (Frank & Mellema 1994; Mellema & Frank 1995). The cause of this density enhancement has been attributed to (a) the gravitational effect of a binary companion, (b) rotation, perhaps amplified by a binary companion, or (c) magnetic fields. These mechanisms have been discussed at this conference (see Livio). This axial symmetry must arise or be enhanced during the PPN evolution. Thus the study of the morphology of PPNe holds the potential to allow us to see how this asymmetry develops.

The fact that the first good candidates for PPNe discovered - AFGL 2688 (Egg nebula) and AFGL 618 - both show a bipolar morphology encourages us that the imaging of PPNe will be fruitful. Direct imaging of additional PPNe has been obtained over the last several years, as discussed below. A polarization study by Trammell, Dinerstein, & Goodrich (1994) obtains results that are, in general, supportive of the results of these imaging studies.

3.2. MOLECULAR-LINE CO

Large objects can be resolved and mapped in CO, and this has been done for IRAS 19114+0002 (Bujarrabal, Alcolea, & Planesas 1992) and 22272+5435 (Dayal *et al.*, this conference). Recent results from the Nobeyama Millimeter Array have been presented by Deguchi (this conference). New millimeter and sub-millimeter arrays will give the ability to resolve the CSEs of many PPNe and to study the physical conditions.

3.3. MID-INFRARED IMAGING

Mid-infrared imaging can allow one to see the dust envelope directly, particularly the inner edge. Recent advances in mid-infrared array technology are being exploited by several groups to study PPNe at 10 and 20 μm. Based upon published studies and preprints, the results of these studies are as follows: (a) two O-rich PPNe have been imaged and resolved, one of which shows a torus (HD 161796, Skinner *et al.* 1994) and one of which is round (IRAS 19114+0002, Hawkins *et al.* 1995); (b) four C-rich, 21 μm sources have been imaged and three resolved: one shows a torus and two are elliptical (Meixner *et al.* 1996). Additional results are presented by Dayal *et al.*, Kömpe, and Van de Steene & van Hoof (this conference), and a summary is given by Meixner in this conference. In addition, a detailed imaging study of the Egg nebula at near-infrared and mid-infrared has been made by Skinner *et al.* (1996).

3.4. VISIBLE & NEAR-INFRARED IMAGING

Two new bipolar PPNe have recently been discovered, IRAS 17150-3224 and 17441−2411 (Hu *et al.* 1993; Kwok *et al.* 1996). In a recently completed study at a resolution of 0.7″ on the Canada-France-Hawaii Telescope, 10 additional, smaller PPNe have been found to be extended, with a typical size of 4″ (Hrivnak *et al.* 1996). The shapes are as follows: elliptical - 6 (including 1 in which the PA varied), round - 3, and 1 with elliptical outer and round inner intensity contours.

Of course new observations have been made at even higher resolution in visible light with the HST. Some of these images, such as the Egg nebula, are familiar because of their wide distribution, while others, such as the Red Rectangle, were shown in this conference (Bond). The high-resolution images of the Egg nebula resolve the bipolar lobes into two pairs of radial "searchlight beams" and a series of approximately concentric arcs, suggesting reflection from dust emitted with a spacing of about 400 years between arcs. These high-resolution studies will help to determine if mass loss is steady or episodic.

These observations make it clear that non-spherical, axially-symmetric morphology is common in PPNe, and that it is developed by early in the transition stage from the AGB to the PN.

4. Star: Chemistry

There have been previous abundance studies of several stars classified as high-latitude F supergiants. These objects are now generally regarded as low-mass post-AGB and differ from those which we are discussing in that they are mostly without massive CSEs (little mid-infrared excess), and probably will not evolve into PNe. The results of the abundance studies of these objects are not as clear as one might have hoped for (see Luck 1993; Van Winckel 1995); while they appear to be metal-poor, the expected carbon and s-process enhancements from the dredge-up of the results of He-burning are not seen. New studies have shown some of these to be binaries, and some of their peculiar chemical abundance patterns have received a nice explanation as chemical fractionation within the context of a binary star model (Waters, this conference).

In this review, we have restricted our discussion to those which we call PPNe (strong mid-infrared excess). For these, several recent abundance studies have been published. These tend to clearly support the post-AGB nature of these objects, and most of them display abundance patterns indicating the products of a third dredge-up. This is seen in particular in the enhancement of carbon and s-process elements, and in some cases in a low metal abundance indicating a Pop II or thick disk population, and

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thus old stars. These results are collected in Table 2. They agree with the expectation of post-AGB stars evolving to become PNe.

TABLE 2. Abundance studies of central stars of PPNe

ID	SpT	log g (cgs)	[Fe/H]	C/O	[C/Fe]	[s/Fe]	Chemistry	Ref.
05341+0852	F6 I	0.5	-1.0	2	+1.0	+2.2	C	(5)
07134+1005	F5 I	0.1	-1.0	3	+1.1	+2.0	C	(3)
		0.5	$\leq$-1.0	$\sim$1	+1.0	...		(6)
HD 161796	F3 Ib	0.3	-0.3	0.8	+0.3	0.0	O	(7)
18095+2704	F3 Ib	1.0	-0.8	0.7	$\sim$+0.5	-0.1	O	(3)
19114+0002	F5 Ia *	1.3	-0.1	...	...	$\sim$+0.7	O	(4)
19500−1709	A2–3 I *	1.0	-0.5	$\sim$1	+0.9	+1.2	C	(2)
22272+5435	G2 Ia	0.5	-0.5	$\sim$12	+1.7	+2.5	C	(1)

* Spectral types assigned on basis of model atmosphere fitting.

References: (1) Zăs, Klochkova, & Panchuk 1995; (2) Van Winckel, Waelkens, & Waters 1996; (3) Klochkova 1995; (4) Zăs *et al.* 1996; (5) Reddy *et al.* 1996; (6) Parthasarathy, Garcia Lario, & Pottasch 1992; (7) Luck, Bond, & Lambert 1990.

5. Star: Variability

Variability in the central stars of PPNe can arise from either pulsations or a binary companion. AGB stars, of course, pulsate with long periods, and there are classes of post-AGB which are known to pulsate - RV Tau (P = 50–150 d, alternating deep and shallow minima, SpT = F–K) and UU Her (P = 40–100 d, small amplitude, SpT = F). Variability, particularly in radial velocity, can arise from a binary companion, and such a companion can be very important in determining an axis of symmetry for the AGB mass loss and the subsequent shaping of the PN.

These reasons motivated us to undertake a high-resolution radial velocity study of the brighter PPN candidates. Nine bright PPNe were observed for radial velocity variations over 5 seasons; all 9 were found to vary, with an average velocity range of 10 km s^{-1}. For 3 of these, a consistent period was found: 18095+2704 (F3 Ib, P = 109 d), 22223+4327 (G0 Ia, P = 89 d), 22272+5435 (G5 Ia, P = 127 d).

To better understand the nature of these objects, and to extend the study to fainter PPN candidates, a photometric study was initiated in 1994. We are presently monitoring $\sim$40 PPN candidates for photometric variability. Some interesting initial results have been found. (1) Almost all of the 40 show low-amplitude light variations, with typical variations of 0.15–0.35

mag in V. (2) Periodic light variation has been found in 9 objects thus far, with periods ranging from 25–146 d. These objects all have spectral types F – G. (3) The 3 with periodic velocity variations also display light variations with the same period, but both the light and velocity curves show changes in the amplitude of the variations. (4) Short timescale variations (< 10 d) have been found in several of the objects, particularly those of early spectral types, O – B. (5) There appears to be a general trend of shorter P with earlier spectral type. The nature of these variations points to pulsations, rather than a binary nature. More details of this study are presented at this conference (Hrivnak & Lu; see also Hrivnak & Lu 1996).

6. Theory & Modeling

Evolutionary models of PPNe must include both the evolution of the star and any ongoing mass loss from the atmosphere. Following the earlier models of Schönberner (1983) are more recent models by Blöcker (1995), Schönberner, Blöcker, & Marten (1995), and Schönberner (this conference) and also models by Vassiliadis & Wood (1994) and Wood (this conference). These evolutionary models derive transitional ages of a few thousand years between the end of the AGB mass loss and the beginning of the PN stage.

Modelling of the SED has been carried out by a few groups, to yield the parameters of the circumstellar dust shells. Most models have assumed spherical symmetry, and have fitted parameters such as the inner dust shell radius and density distribution in the shell, assuming a certain grain size and opacity and a stellar temperature and luminosity (Volk & Kwok 1988, 1989; Gürtler, Kömpe, & Henning 1996). Szczerba *et al.* (1996) recently modelled the SED of IRAS 22272+5435 using PAH and amorphous carbon grains of different sizes and an empirical opacity function to fit the 21 and 30 μm features. With the availability of resolved images, which show some nebulae to not be spherically symmetric, a second constraint is added, the morphology. Recently Skinner *et al.* (1996) fitted an axially-symmetric model to the SED and the bipolar morphology of the Egg nebula. Evolutionary models of the SEDs of PPNe have been carried out by Volk (1992) and more recently by Steffan *et al.* (this conference), assuming spherical symmetry.

7. Conclusions & A Look To The Future

We will list a few brief conclusions drawn from this review of PPNe. We have recently found that almost all of them appear to pulsate. Abundance patterns are observed to fit with those expected for post-AGB stars which have experience a third dredge up. Non-spherical (bipolar or elliptical) morphologies are clearly evident in PPNe, even in the cooler (younger) ones.

These studies will be extended by the new images obtained by HST with WFPC2 and NICMOS, with adaptive optics, and with diffraction-limited observations in the near-infrared and mid-infrared on the new class of 8 m and 10 m telescopes. As we look to the future, and in particular the next PN conference, we also eagerly look forward to the results from ISO to learn more about the chemical and physical properties of the CSEs of PPNe.

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