NEBULAR PROPERTIES OF PROTO-PLANETARY NEBULAE

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ABSTRACT
Recent ground-based observations of cool IRAS sources have led to the discovery of many candidates for proto-planetary nebulae (PPN). These objects have cool dust shells and molecular envelopes reminiscent of the circumstellar envelopes of asymptotic giant branch (AGB) stars. Observations of PPN confirm that the circumstellar envelope ejected during the AGB phase dominates the infrared continuum of post-AGB objects. We suggest that an infrared sequence can be traced throughout the evolutionary phases from AGB to planetary nebulae.

Introduction

It is now established that stars suffer large scale mass loss as they ascend the asymptotic giant branch (AGB). The circumstellar envelope created by the mass loss process often completely obscures the photosphere, making direct observation of the star impossible. It is therefore impractical to trace this part of evolution using the traditional parameters of luminosity and temperature as used in the Hertzsprung-Russell diagram. Observation of the circumstellar envelope presents an alternative method of determining the evolutionary status of a star. For example, oxygen-rich AGB stars have well-developed silicate dust features which change from emission to absorption as the star evolves.\(^1\) There is also evidence that molecular emissions (OH and CO) from the circumstellar envelope also change in a systematic manner.\(^2\) The recent IRAS sky survey has detected infrared continuum emission from thousands of AGB stars, creating a large database from which theoretical inferences can be drawn.

If extensive circumstellar envelopes (with masses up to several \(M_\odot\)) are created on the AGB, then remnants of such envelopes should still be present in planetary nebulae. Kwok\(^3\) has argued that the nebular properties observed in AGB stars should also be detectable in planetary nebulae (PN). There is increasing evidence that many of the circumstellar

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Figure 1. Distribution of AGB stars and young PN in the IRAS colour-colour diagram.
characteristics of AGB stars are indeed present in young PN. Given that this is the case, the study of nebular properties of AGB stars and young PN should allow us to infer observational characteristics of transition objects between the AGB and PN, a previously-unobserved phase of evolution. In this paper, we will focus on the continuum radiation from the circumstellar envelope and attempt to construct a coherent picture of evolution from AGB to PN.

**An infrared sequence in the IRAS colour-colour diagram**

The fact that stars at different phases of evolution on the AGB have unique IRAS colours was first noted by Olnon et al. They found that OH/IR stars with different degrees of variability are distributed along a narrow band on the IRAS colour-colour diagram. More comprehensive studies of AGB stars by van der Veen and Habing and Walker and Cohen showed that Mira variables occupy a part of the colour-colour diagram below the blackbody line. An apparent connection exists between the area occupied by Mira variables and OH/IR stars which can be considered as an evolutionary sequence.

The evolutionary status of oxygen-rich AGB stars can also be classified by their silicate dust features as suggested by Merrill. Figure 1 shows the colour distribution of 196 stars with the 9.7 μm silicate feature in emission and 110 stars with the silicate feature in absorption. We can see that the silicate-emission objects have typical colour temperatures of 300-1000 K, and are clearly separated from silicate-absorption feature objects which have lower colour temperatures (200-300 K). The change of the silicate feature from emission to absorption and the monotonic decline in colour temperature can both be understood as the result of increasing rates of mass loss. If the mass loss rate increases as the star ascends the AGB, then the band in the colour-colour diagram can be interpreted as an evolutionary sequence.

While the IRAS colours of PN are scattered throughout the colour-colour diagram, the situation is quite different if we look at a sample of young PN. In Fig. 1, we have also plotted 51 PN (open squares) with 5 GHz brightness temperatures greater than 1000 K, and 75 PN (filled squares) with brightness temperatures between 100 and 1000 K. We can see that the colour temperatures of these young PN are again lower than those of AGB stars. We can also see a separation in colour between the two groups of young PN. Since a PN with higher surface brightness is probably younger, the trend of monotonic decrease in colour temperature therefore continues all the way from AGB to PN.

This observed colour sequence in fact has two separate physical origins. On the AGB where the mass loss is increasing, the change to lower colour temperature is the result of increasing optical depth in the dust circumstellar envelope. After mass loss has terminated, the decrease in colour temperature is caused by geometric dilution as a consequence of the envelope dispersing into the interstellar medium. As an illustration of the physical process,
we have plotted the theoretical evolutionary tracks for stars of initial mass 8 and 1.5 \( M_\odot \) calculated by Volk and Kwok.\textsuperscript{10}

The most interesting implication of this diagram is the gap between AGB stars and PN. If the above evolutionary scenario is correct, this area should be occupied by transition objects between AGB and PN. Searches for \textit{IRAS} objects lying in this part of the colour-colour diagram could therefore lead to the discovery of such transition objects, or proto-planetary nebulae.

Since the term proto-planetary nebulae (PPN) has sometimes been misused in the literature, we will adopt the following precise definition for PPN.\textsuperscript{11} The beginning of the PPN phase (or the end of AGB) can be identified as the point where most of the hydrogen envelope has been depleted by mass loss. For a star with a core mass 0.6 \( M_\odot \) and envelope mass of \( 10^3 \ M_\odot \), Schönberner\textsuperscript{12} estimates the effective temperature to be \( \sim 5000 \) K. It is reasonable to assume that large-scale mass loss also ceases at this point. The circumstellar envelope will remain neutral until the effective temperature of the central star reaches 30,000 K. When the star begins to emit significant numbers of ultraviolet photons, the envelope will be ionized and we will see the birth of a planetary nebula. The evolutionary phase from \( T_e=5,000 \) to 30,000 K can be defined as the PPN phase.

\textbf{Figure 2} Finding chart of OH17.2-2.0 (PSS E print). North is up and East is left. The infrared position is shown between the two bars.
Ground-based identification of IRAS sources

Since PPN are likely to be infrared sources of low colour temperatures, we have been carrying out a systematic identification program of cool IRAS sources since 1985. To be absolutely certain about the optical counterpart of the IRAS source, all identifications were made at 10 or 20 \( \mu m \). We find that IRAS positions are generally accurate to within 5 arc sec and the identification of the optical counterparts is usually not a problem for sources located out of the Galactic plane. However, for IRAS sources in the plane, actual ground-based identification in the mid-infrared is desirable for the following reasons: (1) the field is often so crowded with red stars that identification at the near infrared wavelengths is not always reliable; (2) many cool IRAS sources have no optical counterparts and one cannot assume a visible star closest to the IRAS position is the counterpart; (3) IRAS positions can sometimes be in error by as much as 1 arcmin.

These problems are illustrated by the following examples. The bright star SAO 187072 is almost right on the IRAS position of 18351-2345. However, ground-based identification reveals that the IRAS source is in fact 11 arc sec south-west of the star.

Figure 2 shows the finding chart of the well-studied PPN candidate OH 17.7-2.0. There are four visible stars in the vicinity of the IRAS position. The IRAS source, however, happens to have no optical counterpart down to \( \sim 18 \) mag and is 3 arc sec away from the nearest visible object.

Obtaining a correct identification is particularly important in the search for PPN. There are many far infrared sources in star formation regions. Mistaking a foreground red star as the counterpart of the IRAS source can easily produce the illusion of a double-peak energy distribution that is the characteristic of PPN.

Search for Proto-Planetary Nebulae

Using the PPN models of Volk and Kwok as a guide, we have identified a number of IRAS sources that have infrared colours that fall between those of silicate absorption objects and young PN (cf. Fig. 1). Figure 3 shows the flux distribution of a nascent PPN. The object (19454+2920) has no optical counterpart (down to \( \sim 20^m \) in \( V \)) and has a colour temperature of \( \sim 170 \) K. However, a heavily reddened photosphere can be seen in the near infrared region. This suggests that the circumstellar envelope of the star is gradually dispersing, allowing the light from the photosphere to emerge.

A more evolved example of a PPN is shown in Fig. 4. In this case, approximately equal amounts of flux are emitted by the circumstellar dust and the photosphere. The brightness of the central star implies that the dust envelope must be optically thin. The large amount of flux emitted by the dust envelope, however, suggests a significant amount of mass in the envelope. The only way that these two facts can be reconciled is if the dust envelope is detached from the photosphere. Also shown in Fig. 4 is a model fit based on a radiative
Figure 3 Energy distribution of PPN candidate 19454+2920. Two blackbody curves are also shown for comparison.

Figure 4 Energy distribution of PPN candidate 22272+5435. The dashed line is a model curve.
transfer calculation of a spherically symmetric envelope. By combining the model results with the observed envelope expansion velocity from CO observations, the time since shell detachment (or the end of AGB) can be estimated. In the case of 22272+5435, this turns out to be \( \sim 151 \) (D/kpc) yr.

Optical spectroscopy of these PPN candidates shows that many have the spectral characteristics of F supergiants.\(^{18,19}\) The supergiant classification of these objects does not imply that they are massive stars, but only indicates their low surface gravity. Further examples of energy distributions of PPN can be found in van der Veen\(^{20}\), Parthasarathy and Pottasch\(^{21}\); Pottasch and Parthasarathy\(^{22}\); Hrivnak, Kwok, and Volk\(^{19}\); Kwok, Volk, Hrivnak\(^{23}\); Larmers et al.\(^{24}\); Waelkens et al.\(^{25}\); and Menzies and Whitelock\(^{26}\).

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Table 1 lists 30 objects that have been suggested to be PPN candidates in the literature. Excluded from this list are a number of objects which have been suggested as PPN candidates but: (i) have uncertain association (e.g. 17277-3506, which is located on the plane and 30 arc sec from the HD 319896); (ii) are binaries (see Waelkens et al., this volume); (iii) are emission line stars (e.g. 17311-4924); and (iv) have an optical counterpart which is a dwarf rather than a giant: these objects could be Vega-like main sequence stars with planetary disks (e.g. HD 143006); (v) are associated with hot stars (e.g. 15373-4220, 17097-3210, 18213-2948); or (vi) are in an area of high background confusion (e.g. 16115-5044, 18135-1456).

Figure 5  Colour distribution of the PPN candidates in Table 1.

Figure 5 shows the colour distribution of these 30 objects. It is clear that they do not all lie in the region between the AGB and PN. Some (e.g. HD142527, HD101584, HD95767) have colours similar to those of evolved PN. Their colours suggest that these nebulae have cooled so much due to expansion that the 12 \( \mu \text{m} \) band is dominated by the photospheric continuum of the still relatively cool central star. This implies that the central star must be evolving extremely slowly. In fact, they may be evolving so slowly that they may not become PN at all. If this is the case, then they should be referred to as post-AGB objects but not PPN (see Waters et al., this volume).
Nebular Properties of Young Planetary Nebulae

Young PN are characterized by small physical size and high electron density. These factors imply that they are likely to have high surface brightness, both in the radio continuum and in the visible. In a recent radio survey of compact PN with the Very Large Array, Aaquist and Kwok\textsuperscript{27} have identified many PN with high radio surface brightness, which are therefore excellent candidates for young PN. When compared to typical PN, the central stars of young PN are likely to be of lower effective temperatures, with a majority of their flux emitted in the visible range instead of in the ultraviolet. As a consequence, a higher fraction of the stellar flux is absorbed by the dust component than by the gas component, and infrared continuum emission from the dust envelope dominates over line emission from the ionized nebula. Due to the higher dust temperature, the silicate emission features may still be observable. Circumstellar molecular emissions (such as OH and CO), which are characteristic of the circumstellar envelopes of AGB stars, may still be present.

![Graph](image.png)

**Figure 6.** Infrared spectrum of the PN M3-35. The circles are ground-based and IRAS measurements. A least-squares fitted blackbody curve to the IRAS points is also shown for comparison. The dashed line shows the level of $f_f$ emission extrapolated from the 5GHz radio fluxes. Note the presence of the 18 $\mu$m silicate feature in the LRS spectrum.

An example of the energy distribution of a young PN is shown in Fig. 6. We can see that emission beyond 5 $\mu$m is dominated by continuum emission from the dust envelope,
and the infrared emission between 1 and 5 μm is consistent with the level of free-free emission extrapolated from the radio. The excess above the continuum at ~20 μm is probably the 18 μm silicate feature. The colour temperature of the dust continuum is consistent with the suggestion that the dust component represents the remnant of the circumstellar envelope of AGB stars.28)

Models of Planetary Nebula Dust Shell Evolution

The observed continuity of infrared properties from the AGB to the PPN phase to PN shows that over this entire evolution, the circumstellar envelope dominates the IRAS observations. Under these circumstances, it is useful to extend the models for AGB and post-AGB dust shell evolution of Volk and Kwok10,17 to study the dust shell evolution during the PN phase. In these models, we have fitted both the Low Resolution Spectra (LRS) as well as the IRAS colours. The LRS provide a major constraint on the models, especially when there are dust features present. The observed LRS continuum also provides a constraint on the dust temperature, in particular when the dust is cool and the first band of the LRS falls on the exponential side of the Planck curve. With only the colours there is no unique way to fit the data. For comparison with the models, LRS were extracted for 170 PN from the LRS database. Attempts were also made to classify these spectra according to morphological properties and observed dust features.29)

A complete model of PN evolution requires consideration of the following components: (1) an evolving central star; (2) dynamical evolution of the nebula; (3) ionization of the nebula; and (4) transfer of stellar energy to the dust and gas components. Once ionization begins, several complications enter into the models. One must consider the nebula as well as the central star for heating of the dust shell. Furthermore, the actual PN shell is shaped by interaction between the remnant AGB wind and the fast wind from the central star.30) There are also the problems of the destruction of dust in the ionized region, mixing of dust and gas in the nebula, etc. A full model including all these processes would be very complicated. As a first step, we have developed a preliminary model which incorporates several simplifying assumptions: (1) the remnant AGB dust shell continues to expand into the interstellar medium without any wind interaction throughout the PN evolution; and (2) the nebula can be treated as a thin layer at the inner edge of the dust shell which absorbs all the stellar photons shortward of the Lyman limit. These assumptions should be relatively good for young PN, where there is strong evidence that the PN shells are ionization bounded.31) These assumptions will begin to break down as the PN evolves.

For the evolution of the central star, we have adopted the Schönberner12) 0.64 M\(_\odot\) post-AGB evolution model. Beginning at the end of AGB with a dust shell of a certain initial optical depth, the shell is allowed to expand away from the star over time. A series of radiative transfer models are calculated with the proper stellar and nebular spectra
heating the dust. At the onset of ionization, the spectrum is calculated including the free-free and bound-free continua plus optical and UV spectral lines suitable for the stellar temperature, with line strengths based on observations of five prototypical nebulae: IC 418, NGC 6543, NGC 6537, NGC 3918, and NGC 4302. The resulting model nebular spectra should be sufficiently accurate to calculate the heating of the dust shell so long as the line distribution at short wavelengths is approximately correct. The model spectra from the radiative transfer program are then used to derive simulated IRAS colours by integrating over the IRAS filter instrumental profiles. We have specifically avoided using the monochromatic flux densities at the IRAS wavelengths to follow the colour-colour evolution because there will be significant colour corrections that change as the PN evolves.

An example of a model spectrum from λ 700 Å to 0.7 mm for a young PN is shown in Fig. 7. There is an almost complete separation of the nebular spectrum in the visible and near infrared and the dust emission in the far infrared. Figure 8 shows the total post-AGB colour-colour evolution of a star with an initial 10 μm optical depth of 20. The model track spans a period of about 5,500 years, by which time the central star has declined sharply in luminosity and has turned on to the white dwarf cooling curve. The track starts at left, below the blackbody line and evolves to the right more or less parallel to the blackbody line during the PPN phase. When ionization begins, there is extra heating of the dust due to the stronger UV flux of the star, causing the track to temporarily turn back to the left. As the shell continues to expand and cool, the peak of the dust continuum shifts to longer wavelengths and the 12 μm band flux becomes increasingly dominated by emission from the gas component. This causes the track to follow a broad curve upward and back to the left, similar to the loop tracks shown by Chan and Kwok.30 There are smaller variations in the colours depending upon the strength of emission lines in the 12 μm band. As the dust shell continues to cool the track evolves toward the upper-left corner of the colour-colour diagram. If the evolution could be followed further, the track would eventually turn down at nearly constant 12/25 colour and approach the colours of a pure nebular spectrum with no dust. However, the rapid decline in total luminosity of the star as it descends to the white dwarf cooling curve precludes the observation of the dust continuum of a PN on this part of the track by IRAS. The faintness of the dust component implies that only a nearby, old nebula could possibly be detected, but such a nebula would likely be spatially extended and thus not a point source to IRAS. By the time the track reaches [25] - [60] ~ 3.0 the stellar luminosity has fallen from the initial value of ~8,300 L⊙ to ~410 L⊙ and the nebula becomes unobservable.

The track shown in Fig. 8 is only one example of the model tracks constructed. The wide area of the colour-colour diagram occupied by PN implies that tracks with different initial optical depths (or mass loss rates at the end of AGB) are necessary to explain the colours of individual PN. One aspect of the evolutionary track to note is that the
Figure 7. Model energy distribution for a young planetary nebula.

Figure 8. Colour distribution of 364 PN with three good IRAS fluxes. The model evolution track is plotted in solid line and the blackbody curve is shown in dotted line.
Schönberger 0.64 M\(_\odot\) model track nearly evolves too far to the right before turning back. More slowly evolving central stars (i.e. those with lower masses) would evolve to colours as a PN which are too red. Therefore we suggest, based upon the colours of the young nebulae in the centre of the figure, that the transition time between 5,000 and 30,000 K is shorter than that given in the 0.64 M\(_\odot\) model of Schönberger.

Conclusions

Primarily as the result of the far infrared window opened by \textit{IRAS}, a clear picture of evolution from AGB to PN is emerging. We now have strong evidence that the circumstellar envelope created by mass loss on the AGB is still present in PN and a continuous infrared sequence can be traced from the AGB to PN. Continuum dust radiation from the circumstellar envelope represents a significant fraction of total energy output for both late AGB stars and young PN. By interpolating between the infrared properties of AGB stars and young PN, the characteristics of PPN can be predicted. In the past several years, \~30 PPN candidates have been identified. The discovery of this "missing link" in stellar evolution represents a significant step forward, and the many papers on PPN presented in this conference attest to the active interest in understanding this phase.

The evolution from Miras to Planetary Nebulae is indeed an interesting phase of evolution, for it encompasses observations over most of the electromagnetic spectrum from radio to ultraviolet. The coupling between the evolution of the central star and the dynamical evolution of the nebula, as well as the radiative interaction between the two, provides us with a rich laboratory for astrophysical research. The field has also matured to the extent that quantitative theoretical predictions can be tested by precise observations. In the coming decade, we can expect further candidates for PPN discovered and studied, leading to a fuller understanding of the late stages of stellar evolution.

\textit{Acknowledgements.} Mr. O. Aaquist worked on the radio survey data discussed in this paper. We also thank Dr. C.Y. Zhang for discussions on the infrared properties of planetary nebulae. This work is supported in part by a grant from the Natural Sciences and Engineering Research Council of Canada, and in part by NASA's IRAS Data Analysis Program funded through the Jet Propulsion Laboratory.

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