On the properties and evolution of proto-planetary nebulae

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Chapter 1

Introduction

1.1 Historical overview

The idea that planetary nebulae (PNe) are formed out of the atmospheres of red giants originates from Shklovskii (1956). His proposal was corroborated by Abell and Goldreich (1966). By comparing the birthrate of PNe with the birthrate of red giants they argued that in fact most intermediate-mass stars go through a PN phase. The objects undergoing the transformation from a red giant on the asymptotic giant branch (AGB) to a PN, the proto-planetary nebulae (PPNe), remained however a ‘missing link’ in stellar evolution. A decade ago only two objects had been identified as probable PPNe (AFGL 618, Westbrook et al. 1975, and AFGL 2688, Zuckerman et al. 1978).

Theoretical studies of the stellar evolution in the PPN phase have been carried out by e.g. Härm and Schwarzchild (1975), Schönberner (1979, 1983), Wood and Faulkner (1986). These studies showed that the transition time should be shorter than \( \sim 10^4 \) yr, so that only few objects are expected to be observable in the PPN phase. The evolution of the circumstellar envelope was discussed by e.g. Kwok and co-workers. To explain the morphology of PNe, Kwok et al. (1978) introduced the ‘interacting-winds model’, which assumes that towards the end of the PPN phase a fast wind emerges from the central star, which sweeps up material from the AGB phase and shapes the future PN. Kwok (1982) argued that the rapid transition from AGB star to PN ensures that many characteristics of the thick circumstellar envelope in the AGB phase may be preserved during PPN evolution, such as the presence of dust features in the infrared, and of molecular radio emission in the CO or OH maser lines.

The infrared sky survey by the IRAS satellite, completed in 1983, lead to a breakthrough in the observational study of PPNe. Cold dust, which mainly radiates in the IRAS wavelength bands, was observed around a number of stars with optical characteristics compatible with a post-AGB nature (e.g. Parthasarathy and Pottasch 1986, Lamers et al. 1986, Trams et al. 1991 and references therein). Habing and co-workers (e.g. Habing et al. 1987, Bedijn 1987) showed that (non-variable) OH/IR stars located in the IRAS colour-colour diagram to the red side of the region occupied by AGB stars are PPN candidates. Subsequent infrared observations (e.g. Van der Veen et al. 1989) and CO and OH observations (e.g. Likkel 1989, Likkel et al. 1991) showed that many sources in this ‘PPN region’ of the IRAS colour-colour diagram have indeed characteristics expected from PPNe.

In recent years about a hundred IRAS sources have been (tentatively) identified as PPNe (e.g. Volk and Kwok 1989 and references therein, Van der Veen et al. 1989,
1. INTRODUCTION

Manchado et al. 1989, García-Lario et al. 1990, Likkel et al. 1991 and references therein, Trams et al. 1991 and references therein). Only a small part of these have been studied in detail. Their properties are quite diverse, and many aspects of PPN evolution are still poorly understood.

1.2 Properties and evolution of PPNe

1.2.1 The central star

At the tip of the AGB intermediate-mass stars reach a luminosity of several thousand $L_{\odot}$. This luminosity is provided by hydrogen burning in a shell around the degenerated C-O stellar core (e.g. Iben and Renzini 1983). Stars at the tip of the AGB have high mass loss rates, of the order of $10^{-5} M_{\odot} \text{yr}^{-1}$, which removes the stellar envelope surrounding the core. When the mass in the envelope is reduced to less than $\sim 10^{-2} M_{\odot}$, the surface temperature of the star increases and the star evolves towards the blue part of the Herzsprung-Russell diagram (see e.g. Schönberner 1983). The hydrogen burning continues at the same rate, so that PPNe evolve at constant luminosity. As the star evolves towards the blue, its mass loss rate is expected to drop drastically, because (i) its surface gravity increases, and (ii) the pulsations which help driving the mass loss can no longer be sustained once the envelope mass has become too small. The speed of evolution is determined by the rate at which the star removes its remaining envelope. Hydrogen burning at the base of the envelope removes about $10^{-7} M_{\odot} \text{yr}^{-1}$ (depending on the stellar luminosity, see e.g. Schönberner 1979). Post-AGB mass loss in a stellar wind can significantly increase the speed of evolution.

Due to their high luminosity and their low mass, the surface gravity and thus the optical characteristics of post-AGB stars are similar to those of young, massive supergiants (Luck et al. 1983). A prominent property of any PPN candidate must be that its optical spectrum is supergiant-like.

1.2.2 The circumstellar dust/gas shell

In the first phase of PPN evolution, when AGB mass loss has just ceased, the AGB dust/gas shell becomes detached from the star and expands with a typical velocity of $\sim 10 - 20 \text{ km s}^{-1}$. The dust at the inner boundary of the shell cools. As a consequence its infrared emission starts to decrease. During the first hundred years only the emission at shorter wavelengths ($\lambda \lesssim 20 \mu m$) diminishes, but as the inner boundary of the dust shell continues to move outwards the emission at longer wavelengths progressively diminishes as well. If a post-AGB wind is present, hot dust in this wind increasingly contributes to the total infrared emission from the object, especially at the shorter wavelengths.

Radio emission in molecular lines is expected to change less rapidly than the infrared emission. Molecular emission from CO, especially in the $J=1-0$ transition, originates at a large distance from the star. The CO ($J=1-0$) emission is not expected to be much affected during the first thousand years of post-AGB evolution. In the higher transitions of CO the effects of post-AGB mass loss may be noticeable. A fine example is the detection by Gammie et al. (1989) of emission from a fast wind in the
CO (J=2–1) and CO (J=3–2) lines in AFGL 618.

OH maser radiation originates at intermediate distances from the stellar surface. In the very first phase of PPN evolution it is not expected to be affected. It still shows the characteristic double-peak profile in the satellite line at 1612 MHz. In later phases of PPN evolution one may observe a decrease in 1612 MHz intensity, while the main lines at 1665/1667 MHz appear (Lewis 1989). A few young PNe have been detected in OH (Zijlstra et al. 1989). Their OH spectra show irregular profiles, often with multiple features. Individual features frequently show circular polarization. Circular polarization is usually not observed in AGB stars.

A significant difference between the circumstellar envelope in the AGB phase and in the PN phase concerns the morphology. The circumstellar shells around AGB stars show a high degree of spherical symmetry (e.g. Bowers et al. 1983, Olofsson et al. 1992). On the contrary, a large fraction of the PNe have a non-spherical shape (Balick 1987). It is not known when or why this transformation takes place.

1.3 Outline of this thesis and main conclusions

This thesis addresses a number of questions in PPN evolution which are still open, such as: when does the AGB mass loss stop, what is the evolution speed in the PPN phase (what is the PPN lifetime), how does the circumstellar envelope evolve, what are the properties of the post-AGB mass loss. To this end we have studied an infrared complete sample of 62 PPN candidates. This sample has been selected from the IRAS catalogue, mainly on the basis of their infrared colours.

The observational material on which this thesis is based is presented in the first chapters. In Chapter 2 the selection of the PPN sample is discussed. The optical and infrared observations carried out for the 42 southern sources in the sample are presented. Each source is briefly discussed. The sources for which optical spectroscopy has been obtained have mainly spectral types M, G and F, which indicates that mainly the younger PPNe are contained in our sample. Chapter 3 deals with CO and OH maser observations of the sources in the sample. The sources which have been detected show the signatures of evolved stars. Several sources show the double-peak OH 1612 MHz profile characteristic of OH/IR stars, but many sources have additional main line emission. Nearly all sources appear to be non-variable over a period of one to five years, in contrast to normal OH/IR stars which do show variability. Quite a number of sources show multiple features in the OH spectra, sometimes circularly polarized. In general the OH observations support the PPN identification of the sources.

Two particularly interesting sources in the PPN sample, which have been studied in more detail, are discussed in Chapters 4 and 5. These studies highlight poorly known phenomena in PPN evolution, such as the origin of asymmetry in the circumstellar envelope, and the onset of a fast wind from the central star. Chapter 4 discusses the source IRAS 17150–3224, associated with a bipolar reflection nebula. It has recently entered the PPN phase. There are indications that the deviation from spherical symmetry developed less than \( \sim 10^3 \) yr ago. The OH maser observations of this source show a relatively large velocity gradient in the stellar wind at large distances from the star. Its OH 1665 MHz maser is strongly circularly polarized, suggesting the presence
of a magnetic field. It is argued that this magnetic field may have played a role in the shaping of the circumstellar envelope.

The object IRAS 08005–2356 is discussed in Chapter 5. It has a fairly bright optical counterpart, which allows spectroscopy at intermediate dispersion. The source shows strong Hα emission. The Hα profile has very broad wings, which seem not directly related with the strong photospheric emission profile. The wings are probably formed in a shell of shocked material, expanding with $\sim 400 \text{ km s}^{-1}$. This may provide direct support for the ‘interacting winds’ model of Kwok et al. 1978. However, this object has spectral type F5I, while the interacting winds model assumes that the fast wind is driven by radiation pressure of UV photons. IRAS 08005–2356 has a very large near-infrared excess, which indicates a large present-day mass loss rate (as does the strength of the Hα profile). If this mass-loss rate continues, the object may turn into a planetary nebula within $\sim 150 \text{ yr}$.

Radiative transfer calculations of circumstellar dust shells in the PPN phase are presented in Chapter 6. These calculations are used in the final chapter, when interpreting the observational data of the PPN sample. As a novelty compared to previous work, the effects of post-AGB mass loss are taken into account.

The interpretation of the observational data is carried out in Chapter 7. The infrared data suggest the occurrence of large post-AGB mass loss rates, typically $\dot{M}_{\text{AGB}} \sim 5 \times 10^{-7} \text{M}_\odot \text{yr}^{-1}$. Such large mass loss rates imply that PPNe lose their remaining stellar envelope in a short time, hence the PPN phase should be short. This is confirmed by modelling the galactic distribution of the PPNe in our sample. The PPN column density perpendicular to the galactic plane is found to be $\sim 1 \text{kpc}^{-2}$ (in the solar neighbourhood). This value includes an extrapolation of the number of PPNe satisfying our selection criteria to the total number of PPNe. This extrapolation is performed in appendix A. The derived column density translates into a duration of the PPN phase of $\sim 10^3 \text{ yr}$.

The stellar temperature at which the AGB wind stops is not known. In theoretical calculations of post-AGB evolution it is usually assumed that the wind stops at a well-defined stellar surface temperature, but our observations show that this is not the case. It is found that AGB mass loss stops at a range of surface temperatures, corresponding to spectral types K and (late) F.

A discrepancy is found between the reddening of the sources and the extinction at optical and near-infrared wavelengths, if this extinction is calculated from the infrared excess, assuming absorption and reradiation in a spherically symmetric circumstellar dust shell. This may be due to anomalous properties of the circumstellar dust grains, but we favour an interpretation where the effect is due to asymmetry in the circumstellar envelope. As nearly all sources show the effect, the asymmetry should have developed before the PPN phase.

During a search for PPN candidates in the IRAS catalogue I unexpectedly was confronted with a relatively large number of RV Tau stars. These stars have been considered PPN candidates by Shklovskii (1956) and e.g. Jura (1986). Several inconsistencies regarding space distribution and lifetime were found. In appendix B these inconsistencies are discussed. It is found that the column density on the galactic plane
of RV Tau stars is $\sim 6 \text{kpc}^{-2}$. This value implies that a large fraction of the RV Tau stars within a few kpc from the sun has not yet been discovered. The life-time of RV Tau stars is found to be $\sim 10^4 \text{yr}$.

The chapters in this thesis are written as self-contained articles, published (Chapter 5) or to be submitted. This results in some overlap, especially in the introductory sections. In case papers published after printing of this thesis deviate from their equivalent chapters in this thesis, these papers supersede the thesis versions.

References

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