THE EVOLUTION OF THE COMMON PLANETARY NEBULA

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1. INTRODUCTION

When we look at evolutionary aspects of PNe, we hope to test our ideas and understanding of the origin of PNe - i.e. why and how gas is expelled from the progenitor star - and of the processes relevant in the evolution of the nebula as well as the central star.

Evolutionary aspects of the central stars are covered elsewhere in this Symposium, so let us look at what we can observe in the nebulae that tells us about their evolution. As the PN's lifetime of about 30000 yrs is much greater than the time basis for the observations, we mainly depend on comparing objects of different ages. Expansion velocities are of the order of 20 km/s, so the radius R of a nebula can be taken as a measure of its age. It depends however on the assumed distance. Also, we not only assume that all PNe have a common origin and history, but we also ignore the presence of multiple shells in many PNe.

The basic quantities of a PN, formed of gas expanding away from and photoionized by the central star, are:

density n   velocity v   ionization x

The state of the gas is further described by the electron temperature, which in PNe however is always near 10^4 K. There are two ways to study these nebular properties: First, from observations integrating over the nebula's face one gets average values N(R), V(R), X(R) for a nebula of size R. Secondly, for angularly resolved objects one may try to derive the radial dependences n(r), v(r), x(r) and compare them with distributions n(r,t) etc. from theoretical models.

Let us have a first look at the density: The average electron density decreases with increasing nebula size.

S. Torres-Peimbert (ed.), Planetary Nebulae, 523–530.

The measurements can be fitted quite well with a simple law $N\ R^3 = \mathrm{const}$ (Fig.4 of Schmidt-Voigt and Köppen, 1987b, henceforth SKb). The very crude model of a spherical nebula whose ionized mass M_{ION}, outer radius R and thickness D, yields: $N\ R^3 \propto M_{ION} / (D/R)$. So the observed dependence N(R) can be understood in terms of a nebula with constant ionized mass, if its shell geometry D/R remains also constant. What do **proper** models tell us?

2. ASSUMPTIONS OF NEBULAR MODELS

Numerical models which solve the equations for the flow, ionization, and energy balance of the nebular gas at various levels of sophistication have been constructed by Mathews (1966), Sofia and Hunter (1968), Ferch and Salpeter (1975), Okorokov et al.(1985), Bedogni and D'Ercole (1986), Schmidt-Voigt and Köppen (1987a). The physical assumptions used were (the degree of underlining denotes the degree of importance in PN):

- Geometry: spherical symmetry
- Forces: thermal pressure, radiation pressure(gas+dust), gravity
- Ionization: by photoabsorption, electron collisions
  - Treatment:
    - complete ioniz. (O.K. for principal effects)
    - ioniz.equilibrium (O.K. for main nebula only)
    - time dependent (best)
- Central Star:
  - Parameters: theor.evolut.tracks
  - Spectra: blackbody (!!)
- Energy: photoabs.,compression, heat conduction, line+contin.emission, expansion, coll.ioniz.
  - Treatment:
    - isothermal (O.K. for most purposes)
    - balance of gains=losses (better)

A model is characterized by its initial conditions, in particular the initial distribution of density and velocity. These can be described by three major periods of mass loss which the central star underwent:
(1) as a red giant it had a slow ($\sim$10 km/s) "AGB wind".
(2) at the end of its life on the AGB, it might expel matter in the form of a short, slow, massive "superwind".
(3) central stars have fast (2000 km/s) winds.
The mass loss rates (velocities, duration,...) of each component are considered to be free parameters.

The interface between the fast wind and the slowly moving gas expelled earlier was studied by Lazareff (1981), Bedogni and D'Ercole (1986): A shock develops which separates an inner region of unshocked fast wind matter and an outer region of shocked, very hot gas. The pressure by this "hot bubble" prevents the exterior nebular gas to flow towards the central star, and is thus responsible for the formation of the central cavity typical for PNe (Mathews, 1966; Okorokov et al. 1986; SKa). Although the structure and physics of this interaction between fast wind and slow nebula do deserve more detailed studies, it is often sufficient and numerically more convenient to take into account the pressure as an inner boundary condition for the nebula (cf. Mathews, 1966; SKa; analytical model of Volk and Kwok, 1985). SKa found that the fast wind - as massive as observed - is responsible essentially only for the central cavity. Therefore we shall concentrate in the following on the exterior regions where superwind and AGB wind material form the visible PN shell.

In our discussion of the evolution of different types of models we shall use this classification:

1 Wind Model: essentially superwind ejecta, representing the idea of PN formation in a single, sudden event. Very dilute AGB wind; fast wind present to make inner cavity. Termed "non-accreting 3WM" by SKa,b).

2 Wind Model: no superwind; only AGB and fast wind interact, as proposed by Kwok et al. (1978).

3 Wind Model: superwind and AGB wind form nebula (see below), fast wind present.

3. PATTERNS OF THE GAS FLOW

According to theory (Schönberner, 1981) a star leaving the AGB takes about 3000 yrs to heat up before it can ionize hydrogen to make the surrounding nebula visible. Little is yet known about this first phase of nebular evolution. The gas is still neutral and probably rather cool, so thermal pressure is expected to be less important than radiation pressure on gas and dust (c.f. Okorokov et al., 1986). The dust is heated by the stellar continuum and its radiation in the infrared should help investigating this "neutral phase".

Then the nebula becomes ionized, and soon after a nebula of a typical mass of 0.3 $M_\odot$ is completely ionized. Now the nebula can well be treated as a shell of ionized gas with a temperature of about 10^4 K. The increased thermal pressure dominates the further evolution of the shell: The outer boundary of the nebula moves into the surrounding AGB wind remnant with a velocity that increases with increasing density contrast across the boundary.

Thus a 1WM expands (in the extreme case: into vacuum) with a greater speed than a 3WM which runs into a denser AGB wind. The velocity increases toward the outer boundary, while the density shows a decrease (Fig. 2 in SKa).

Though the velocity profile in a 3WM (Fig.4 of SKa) also shows an increase with radius, the density profile changes over from an initially decreasing function to an increasing one. This change of slope is caused by the mass flow across the shock from the AGB wind into the nebula. The accretion rate for the whole nebula

$$\dot{M}_{ACC} = \dot{M}_{AGB} (V_{S} - V_{AGB}) / V_{AGB}$$

depends on the shock velocity V_{S} and on the velocity V_{AGB} and mass loss rate $\dot{M}_{AGB}$ of the AGB wind. The time during which the nebula has swept up as much mass as its original mass (i.e. M_{SW} of the superwind ejecta):

$$t_{SWEEP} = M_{SW} / \dot{M}_{ACC}$$

is the age when the density profile changes its slope. If this occurs during the visible life of a nebula, the object then has a structure distinctly different from a 1WM. This condition is the proper definition of a 3WM as opposed to a 1WM (SKa, SKb used the terms (non-) accreting 3WM).

In a 2WM the nebula is created solely by the accretion process, and its structure resembles that of a developed 3WM: the density profile always increases with radius; the velocity increases, and tends to be smaller than in 3WMs.

How do these types of models compare with observations? Since most PNe show rather well defined outer borders, 2WM and 3WM because of their increasing density profile seem more appropriate than 1WM which have a rather extended decline of their surface brightness.

The decline of the average density **N(R)** - Fig.7 in SKb - is quite well reproduced with almost any model. There is a tendency for 1WMs to disperse too quickly and 2WMs too slowly.

Nothing is known about the density profile **n(r)**, which should provide another test between 1WM and 2WM/3WM.

The observed expansion velocities **V(R)** - Fig.1 of SKb - are not reproduced by the rapidly expanding 1WMs. 3WM and the even slower 2WM fit the velocity pattern much better.

Weedman (1968) found that the velocity **v(r)** within the nebula increases linearly with radius. Unfortunately, all types of models show this type of velocity profile, so no distinction can be made with this parameter.

4. IONIZATION

To understand the gas flow one essentially needs to take into account the fact that the star has become hot enough to ionize tha nebula. The degree of ionization, however, depends on the stellar temperature and luminosity, both of which vary strongly with time. Therefore, the ionization reflects the actual stellar evolution more closely. The star's temperature first rises quickly, goes through a maximum, after which the stellar energy sources are exhausted and the star starts to cool off very slowly. So, for each value of temperature there are two possible places in the HR-diagram where a star might be. To resolve this ambiguity, one can make use of the fact that the maximum temperature in Schönberner's (1981) tracks occurs at a stellar absolute visual magnitude of about 5, and thus separate observed objects into two groups:

*** the UPs: nebulae with bright central stars that can be tought of still heating up.

*** the DOWNs: nebulae with faint stars which we interpret as already cooling down.

To measure the volume averaged degree of ionization, the HeII/Hß ratio is attractive for a first step: Recombination lines are much less sensitive to nebular temperature and density than collisionally excited lines. If the nebula is optically thick in both H and He^+ Lyman continua, these lines count the number of ionizing photons from the central star. Finally, since both elements are the main contributors to the opacity, they set up an opacity and ionization structure which the other elements have to follow.

The evolution of the line ratio up to the time of the maximum stellar temperature, as observable in the UP nebulae (Fig.2 of SKb), is dominated by the time scale of the star's heating up; differences in models are negligible. The HeII/Hß ratio increases until the nebula becomes optically thin first in H, then also in He^+ continuum when it levels off. Since the stellar time scale is a steep function of the star's core mass, one obtains a very good leverage on this mass: SKb find Schönberner's hydrogen burning stars of 0.6 to 0.64 $M_\odot$ to give the most favourable fit.

After the temperature maximum the number of ionizing photons drops rather sharply. From now on, the stellar evolution proceeds at snail's pace, so one may consider all stellar parameters as constant for the rest of the nebula's life. Therefore, the evolution of the ionization is now strongly determined by the properties of the nebular models (Figs.3, 4 in SKb).

The observed line ratio of DOWN objects is lower than that of the late UPs, optically thin in both H and He^+. Therefore, the nebulae must not only recombine partially, but also keep this lower degree of ionization. Only nebular models that meet **both** conditions can be acceptable.

1WM that are massive enough to recombine (both in H and He^+) fail to meet the second constraint: as the nebula expands and its density decreases, the constant star is able to ionize a greater mass. The nebula eventually become optically thin in H again, the HeII/Hß ratio increases.

2WM and 3WM of suitable and reasonable parameters can be found that have accreted enough matter to recombine when the star's photon output drops. They are also able to meet the second condition: their mass increases by accretion at such a rate that the total number of recombinations remains constant, despite the decline in density. Consequently, the ionization structure in the shell does not change (Fig.5 of SKa). SKb find as most suitable models either a

3WM: $M_{SW} = 0.1\ M_{\odot}$, $\dot{M}_{AGB} = 6\ 10^{-6}\ M_{\odot}/yr$

or a

2WM: $\dot{M}_{AGB} = 10^{-5}\ M_{\odot}/yr$.

The 3WM has the advantage that it explains the high Zanstra temperatures of rather small nebulae better than 2WM (Fig.6 in SKb).

In this way the low ionization of old PNe enables us to measure the mass loss rate on the AGB which are of the order of $10^{-5}\ M_{\odot}/yr$.

Additional information can hopefully obtained by looking at other line ratios. Also, the distribution of ions in the nebula might be tried, especially since the nebula can well be assumed to be in ionization equilibrium and its structure can be well calculated with static models.

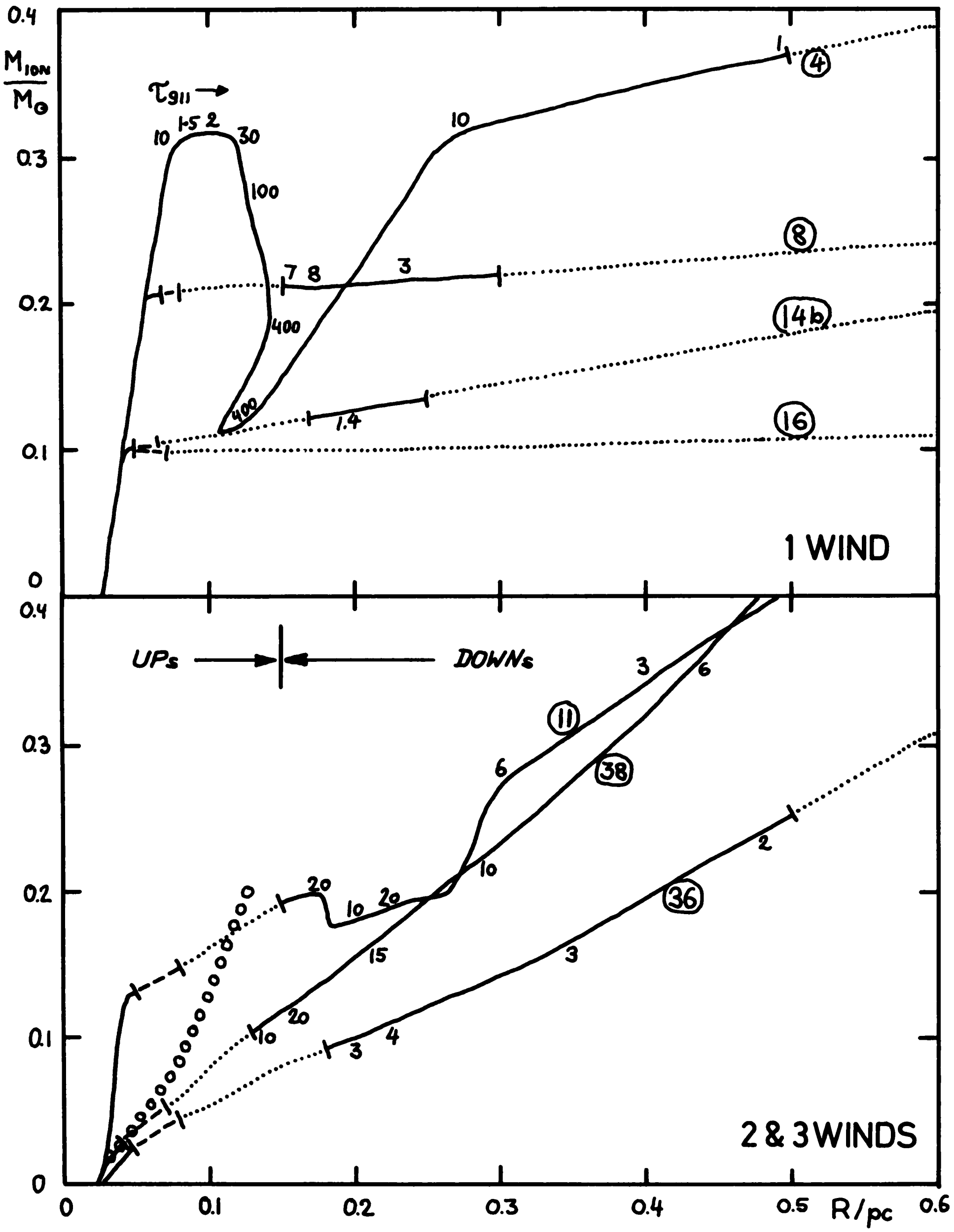
5. MASS RADIUS RELATION AND OPTICAL DEPTH

The various types of models can be nicely characterized by their mass-radius relation, which for almost all models of SKb can be well represented by:

$$M(R) = M_{SW} + 10^{5}\ \dot{M}_{AGB}\ R$$

(in the convenient units of solar masses, years, parsec). In the following figures we show the ionized mass-radius relations for a number of models from SKb (labelled by their number). Full lines show when the nebula is optically thick in H - the adjoining numbers are the optical depths at 911 Å - dotted lines when it is optically thin both in H and He^{+}. When the nebula is optically thin or slightly thick, the ionized mass equals the total mass, and the above relation holds also for the curves in the figure, exept for the time when the ionization front transverses the nebula for the first time ($R < 0.07$pc). Exept for No.4, a rather massive 1WM, the models shown then become optically thin in H, then in He^{+}. When the star's (here: Schönberner's 0.644 track) photon output drops sharply, the nebulae recombine, and become (moderately) optically thick in H again. In Nos.4 and 11 the mass is so large that the optically depth gets rather large and the ionized mass decreases appreciably. Thereafter the nebula enters the "DOWN" phase ($R > 0.15$pc) and finally becomes optically thin in H and He^{+} again. As a consequence of their high accretion rate, 2WM and 3WM are able to stay optically thick much longer than 1WM.

The empirical ionized mass-radius relation from Phillips



Ionized Mass–Radius Relation for models of SKb with the 0.64 $M_\odot$ star, labelled by circled numbers. The nebula is optically thick in H (full line), and thin in H and He^+ (dotted). The numbers are the optical depths at 911 Å.

and Pottasch (1984) (open circles) could be explained by a 2WM with $\dot{M}_{AGB} \approx 2\ 10^{-5}$ $M_{\odot}$/yr.

6. FINAL REMARKS

To summarize:

** From younger nebulae (UPs) one can determine the stellar evolutionary time scale.

** Old, extended nebulae (DOWNs) are extremely useful to probe into the initial conditions and to measure the AGB mass loss rate.

** Accretion from a rather massive AGB wind is a most important process in the formation of PN shells.

Apart from the problems and possibilities already mentioned, here are some more items for our shopping bag of things to be done:

** Interaction of fast wind with slow nebula. Are the obnoxious filaments created by this process?

** Influence of stellar wind on central star evolution.

** Use of proper stellar flux distributions rather than blackbodies.

** Departure from spherical symmetry. What happens when the nebula is optically thin in one direction but thick in another?

** Multiple shells: constraints on the ejections.

7. ACKNOWLEDGEMENTS

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