EFFECTS OF STELLAR MASS LOSS ON THE FORMATION OF PLANETARY NEBULAE

Sun Kwok
Herzberg Institute of Astrophysics
National Research Council of Canada
Ottawa, Ontario, Canada K1A 0R6

I. INTRODUCTION

Over the last decade, stellar mass loss has become recognized as an important factor in the evolution of stars. The magnitude of the mass loss rate is found to be greatest amongst high luminosity stars at both the red and blue sides of the HR diagram. Planetary nebulae (PN), which result from an evolutionary phase during which the parent star traverses from the red side to the blue in a relatively short time scale, are likely to be affected by these processes. In this talk, I shall review the mass loss processes relevant to the PN phase and discuss their affects on the formation and evolution of PN.

II. RED GIANT MASS LOSS

On the basis of the luminosities of the central stars of PN Paczyński (1971) suggested that asymptotic giant branch (AGB) stars undergoing double-shell burning are the immediate progenitors of PN. These progenitors would have core masses between 0.6-1.4 $M_\odot$ and luminosities from 5×10^3 to 5×10^4 $L_\odot$. At about the same time, observers in the infrared and microwave spectral regions discovered that AGB stars are often surrounded by extensive circumstellar (CS) envelopes (Gehrz and Woolf 1971, Wilson and Barrett 1968, Solomon *et al.* 1970). Analyses of the molecular line (OH, CO etc) spectra of such CS envelopes soon reveal that they are produced by continuous stellar winds (Morris 1975; Elitzur, Goldreich and Scoville 1976; Kwok 1976).

The lower half of the luminosity range assigned to PN progenitors is occupied by Mira variables often characterized by 9.7 μm silicate emission (Merrill 1977) and OH/SiO maser emissions. Although mass loss rates can be derived from these observations (and to a lesser extent by optical observations of CS lines), the best estimates are probably those obtained from CO observations. The solution to the CO radiative transfer problem is well developed (Kwan and Hill 1977, Morris 1980, Kwan and Linke 1982) unlike that for the dust continuum case (see e.g. Jones and Merrill 1977) and the molecule distribution does not suffer

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from the ionization structure difficulties of the optical case. The advantage of solving the excitation problem for thermal emission rather than maser emission is obvious. Modern millimeter-wave technology also allows the observation of both the CO J=1→0 and J=2→1 (as well as ^{13}CO) lines, which helps to further constrain the model parameters. The most comprehensive CO observations are by Knapp *et al.* (1982), who observed ∿12 Mira variables, finding mass loss rates ranging from 7×10^{-7} to 6×10^{-6} $M_\odot yr^{-1}$. We should note that these are lower limits to the mass loss rate for they are derived assuming all carbon atoms are locked in CO. Nevertheless, these rates are already much greater than the corresponding nuclear burning rates (6×10^{-8} $M_\odot yr^{-1}$ for a Mira with a core mass of 0.6 $M_\odot$) as well as the rates derived from the Reimers formula (Reimers 1975) which are commonly adopted in stellar evolution calculations (e.g. Renzini 1981).

Although no obvious optical counterparts exist in our Galaxy for PN progenitors in the upper half of the luminosity/mass range, a good case can be made for the many infrared objects discovered in the IRC and AFGL surveys (Neugebauer and Leighton 1969, Price and Walker 1976) as possible candidates. A large number of these IR stars have been found to be OH and CO sources depending on whether the underlying star is oxygen or carbon rich. The optically thick dust envelopes of these stars (evidenced by their low color temperatures and, in the case of oxygen rich objects, by the presence of silicate absorption features) indicate that the mass loss rates ($\dot{M}$) must be very high. Werner *et al.* (1980) estimate $\dot{M}$ to be between 5×10^{-6} - 7×10^{-5} $M_\odot yr^{-1}$ for OH/IR sources in the luminosity range of 2×10^3 - 3×10^4 $L_\odot$. Analysis of CO line emission find $\dot{M}$ up to 10^{-4} $M_\odot yr^{-1}$ for AGB stars with luminosities of several times 10^4 $L_\odot$ (Knapp *et al.* 1982). The qualitative correlation between L and $\dot{M}$ suggests stars approaching the tip of the AGB have increasing mass loss rates, although the exact cause (suspected by some to be pulsation related: Wood 1979, Willson 1981) is not understood.

The wind velocities are also found to be higher in supergiants than in Mira variables (Dickinson *et al.* 1975, Cahn and Wyatt 1978). This seems to imply that radiation pressure on grains determines the dynamics of CS envelopes but doubts remain as to whether this mechanism can initiate mass loss (cf. Castor 1981).

Due to the uncertainties in our theoretical understanding of the mass loss mechanism, it is difficult to derive a mass loss formula from first principles at this time. As an alternative, I have attempted to evaluate the effects of mass loss on AGB stars using an empirical formula. The mass loss formula adopted ($\dot{M} = 10^{-13}[L/L_\odot]^2[M/M_\odot]^{-2}$ $M_\odot yr^{-1}$) is no more than a empirical representation of the molecular line results, covering the range of mass loss from $\lesssim10^{-6}$ $M_\odot yr^{-1}$ for low mass Miras to ∿10^{-4} $M_\odot yr^{-1}$ for high-luminosity IR objects. Evolution of stars with masses 1,2,3,5 and 7 $M_\odot$ are calculated in Figure 1, starting at the beginning of double-shell burning. The core mass-luminosity relationship given by Iben (1981, eq. [3]) is used. With this mass loss formula, the upper main-sequence-mass limit for a white dwarf is

$\sim 7\ M_\odot$, consistent with the observed limit found by Romanishin and Angel (1980).

Constant period curves for fundamental pulsators are also plotted, using the period-mass-radius relation given in Willson (1982) and the luminosity-effective temperature relation given by Wood and Cahn (1977), eq. [6]). Figure 1 shows that the very long period ($P > 1000^d$) variables discovered in OH (Herman and Harbing 1981) and in the infrared (Engles, Schultz and Sherwood 1981) can be produced by high-mass (2-7 $M_\odot$) stars undergoing rapid mass loss. Similar plots for first overtone pulsators suggest that short period ($P < 300^d$) variables are probably best explained by low-mass ($< 3M_\odot$) stars pulsating in the first overtone.

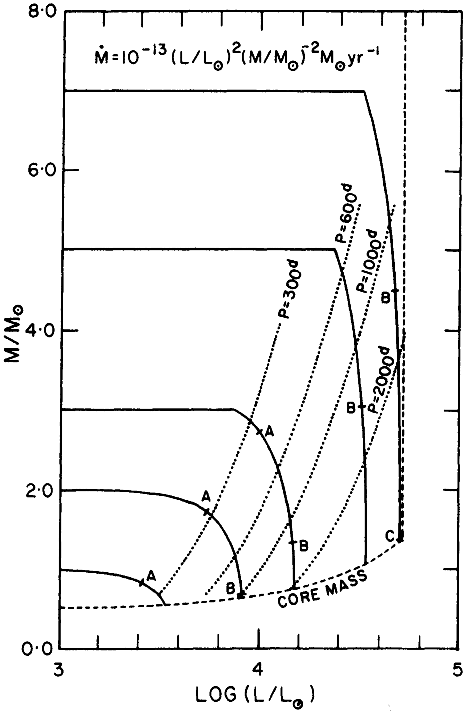

Fig. 1. Evolution curves for AGB stars with initial masses 1, 2, 3, 5 and 7 $M_\odot$. The dash line represents the core mass-luminosity relationship. Points A, B and C correspond to locations where $\dot{M}=10^{-6}$, 10^{-5}, 10^{-4} $M_\odot yr^{-1}$ respectively.

Evolutionary curves similar to those presented in Figure 1 can also be obtained by using the Reimers formula with a large coefficient ($\eta=2.5$). However, in this case the maximum mass loss rate by any AGB star under 7 $M_\odot$ does not exceed 5×10^{-5} $M_\odot yr^{-1}$.

The importance of steady mass loss on the evolution of AGB stars cannot be overemphasized: e.g. according to the mass loss formula adopted in Figure 1, the entire envelope of a 7 $M_\odot$ star can be lost in less then 1 million years! *VLA* observations by Bowers, Johnston and Spencer (1981) find *minimum* sizes for the CS envelopes of 20 OH/IR stars to range from 10^3 to 10^4 A.U. OH phase-lag measurement by Jewell, Webber and Synder (1980) find the size of the envelope of IRC +10°011 to be 5×10^3 A.U. Knapp *et al.* (1982) also determine the size of the CO envelope of IRC +10°216 to be $>5\times10^4$ A.U. All these observations suggest that the CS envelopes cannot be the result of a short ($\lesssim 10^3$ yr) episode of sudden activity but rather are the result of continuous steady mass loss. It is entirely possible that steady stellar winds can completely remove the envelopes of AGB stars without invoking an instability strip of the kind proposed by Wood and Cahn (1977)

III. WINDS FROM CENTRAL STARS OF PLANETARY NEBULAE

The importance of winds from central stars of PN in preventing material backfill was recognized as early as 1966 by Mathews (1966). Recent *IUE* observations (reviewed in detail by Heap and by Perinotto in this conference) have shown that winds from central stars are much more common than previously thought. Heap (1982) has suggested that central stars with a luminosity to mass ratio >11,000 will have a wind. Combining this empirical criterion with the Paczyński core mass-luminosity relationship, we have a lower central-star mass limit of $\sim 0.65\ M_\odot$. Although the mass loss rates are still rather uncertain, the wind velocities can be accurately measured and have been found to range from 2000 to 8000 km s^{-1} (Heap 1982). Central stars with higher temperatures are also suspected to generate higher velocity winds. It is easy to show that such high velocity winds carry a significant amount of momentum and energy (compared to those observed in PN shells) and should have an important effect on the dynamical evolution of PN.

IV. INTERACTION OF STELLAR WINDS

The importance of red-giant mass loss in the formation of PN is obviously dependent on the transition time from red giant to PN. Using the minimum envelope masses of red giants on the AGB (10^{-3}-$10^{-2}\ M_\odot$, see Figure 2 in Paczyński 1971) and the nuclear burning rate (6×10^{-8}-$5\times10^{-7}\ M_\odot yr^{-1}$ for stars with core masses between 0.6 and 1.2 $M_\odot$, Paczyński 1971) it can be shown that the transition is relatively rapid, particularly for high mass stars. Renzini (1981) has also convincingly argued that this transition time cannot be longer than the expansion time of PN ($\sim 10^4$ yr) otherwise the nebulae will not be ionized before it disperses into the interstellar medium.

Given the short transition time scale, the extensive circumstellar envelope created by steady mass loss during the AGB should not be neglected in the treatment of the formation process of PN, regardless of the ejection mechanism. A suddenly ejected PN shell can easily sweep up a fraction of a solar mass of wind material over the lifetime of a PN and what we observe as PN can in fact consist mainly of wind material left over from the AGB phase. This possibility has been evaluated by Kwok, Purton and FitzGerald (1978) and by Kwok (1982) who explore the extreme case where there is no sudden ejection and the steady red-giant wind can persist until the exposure of the hot core. UV photons from the core will then exert pressure via resonance lines on the gas and a new fast wind initiated. This new wind will soon interact with the remnant red-giant CS envelope and, like a snow plow, creates a dense shell at the interface of the two winds.

Assuming that PN is made up exclusively of wind material then the mass of the shell (M_s) is no longer a constant over time. In fact,

$$M_s = \left(\frac{\dot{M}}{V} - \frac{\dot{m}}{v}\right) R_s(t) - (\dot{M} - \dot{m})\, t \qquad (1)$$

Where $\dot{M}$ and $\dot{m}$ (V and v) are the mass loss rates (velocities) of the red-giant and PN-central-star winds respectively. When the transition time (τ) is taken into account, M_s is given by:

$$M_s(t) \simeq \left(\frac{\dot{M}}{V} - \frac{\dot{m}}{v}\right) R_s(t) - \dot{M}t + \dot{m}\left(t - \frac{V\tau}{v-V}\right) \qquad (2)$$

where $t=0$ is when the red-giant wind stops and $t=\tau$ is the time when the central-star wind begins. In the approximation that the collision of the two winds is totally inelastic and all the excess energy is radiated away, R_s quickly approaches an equilibrium velocity V_s:

$$V_s = \frac{(\dot{M}-\dot{m}) + (v-V)(\dot{M}\dot{m}/vV)^{\frac{1}{2}}}{(\dot{M}/V - \dot{m}/v)} \qquad (3)$$

Since the central-star wind carries a significant amount of mechanical energy, it is possible that not all of its energy can be radiated away, especially during the later stages of PN expansion when the density is low. A high temperature zone may develop due to shock heating and thermal gas pressure (p) may become an important term in the force equation. Assuming no radiative losses, we have

$$\frac{d}{dt}\left[M_s(t)\frac{dR_s(t)}{dt}\right] = \dot{m}\left(v - \frac{dR_s}{dt}\right) + \dot{M}\left(\frac{dR_s}{dt} - V\right) + 4\pi R_s^2(t)\ p(t) \qquad (4)$$

The internal energy of the hot region can be written as:

$$E(t) = 3/2(4/3\pi R_s^3)p(t) \qquad (5)$$

and the energy balance of the hot region is

$$\frac{dE(t)}{dt} = \tfrac{1}{2}\dot{m}v^2 - 4\pi R_s^2(t)p(t)\frac{dR_s}{dt} \qquad (6)$$

Substituting (1) into (4), we can obtain similarity solutions to (4), (5), (6):

$$\begin{aligned} E &= at \\ R_s &= V_s t \\ p &= ct^{-2} \end{aligned} \qquad (7)$$

where V_s is the root of the cubic equation:

$$\left(\frac{\dot{M}}{V} - \frac{\dot{m}}{v}\right)V_s^3 - 2(\dot{M}-\dot{m})V_s^2 + (\dot{M}V - \dot{m}v)V_s - \frac{\dot{m}v^2}{3} = 0$$

and

$$c = \frac{\frac{1}{2}\dot{m}v^2}{6\pi V_s^3}$$

$$a = 2\pi V_s^3 c \qquad (8)$$

Figure 2a shows V_s as a function of $\dot{m}$ for the momentum- and energy-conserving cases. We can see that the derived expansion velocities are comparable to observed values. Robinson, Reay and Atherton (1982) have found evidence for increasing values of V_s with R_s. This could be the result of increasing strengths of the central-star wind or the result of a change from momentum- to energy-conserving approximations.

If we accept the result that $dR_s/dt \doteq$ constant, (2) can be written as:

$$M_s \sim \dot{M}\left(\frac{1}{V} - \frac{1}{V_s}\right)R_s - \dot{M}\tau \qquad (9)$$

This can be compared with the empirical M_s-R_s relationship found by Maciel and Pottasch (1980)

$$M_s(M_\odot) = 1.225\ R_s(\mathrm{pc}) - 0.0123 \quad (10)$$

Comparison of (10) and (9) shows that $\dot{M}\tau \sim 0.0123\ M_\odot$ and $\dot{M}(1/V - 1/V_s) \sim 1.2\times10^{-6}(M_\odot yr^{-1})/(km\ s^{-1})$, which can be satisfied by, e.g. $\dot{M} \sim 2\times10^{-5} M_\odot yr^{-1}$, $V \sim 10$ km s^{-1}, $V_s \sim 25$ km s^{-1} and $\tau \sim 600$ yr. Although the consistency of (10) with the interacting winds model may be coincidental, it remains that the existence of

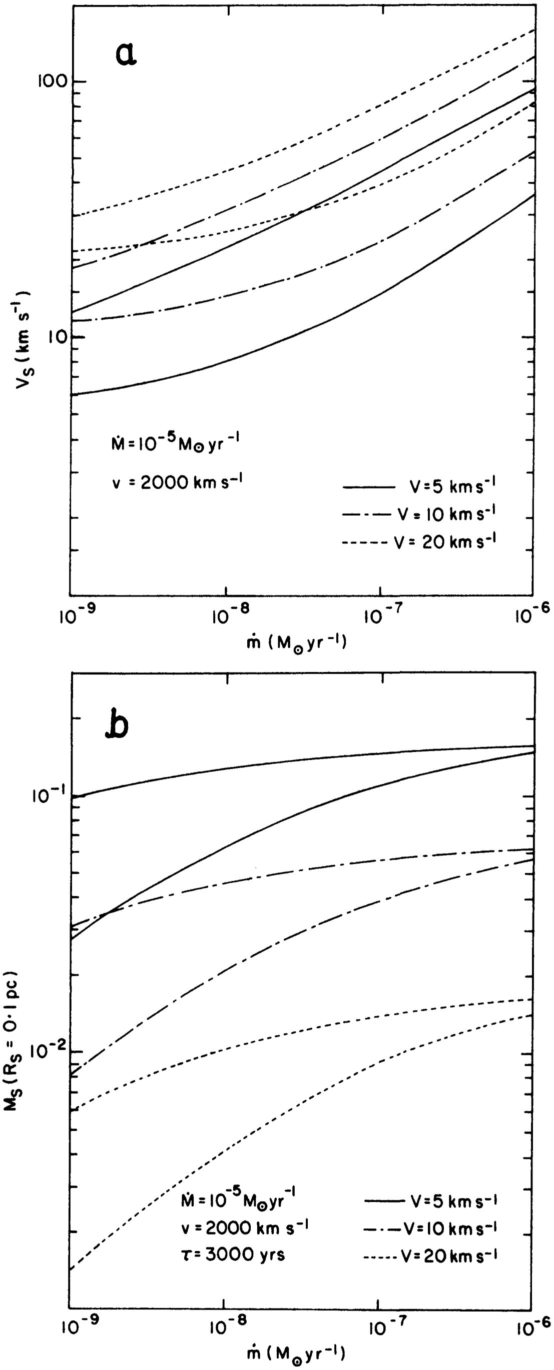

Fig. 2. V_s and M_s as functions of $\dot{m}$. The upper and lower curves of each pair correspond to the energy- and momentum-conserving cases respectively.

such an M_S-R_S relation is difficult to understand in the conventional sudden ejection model.

Figure 2b shows M_S as a function of $\dot{m}$ at the time which $R_S = 0.1$ pc. τ is assumed to be 3000 yr. These curves generally shift upward with increasing $\dot{M}$ and decreasing τ as given by (9).

V. ARE PN FORMED BY SUDDEN EJECTIONS?

Conventional theories of PN formation all rely on sudden ejections due to unstable envelope relaxation oscillations and the problems associated with these models have been discussed in recent reviews by Roxburgh (1978) and Wood (1981). A recent model by Tuchman, Sack and Barket (1979, hereafter TSB) expands on the previous pulsational instability models (Smith and Rose 1972, Wood 1974) and suggests PN is the result of repetitive ejections with exponentially decaying amplitudes over $\sim 10^3$ years. As in Wood and Cahn (1977), TSB also consider PN ejection as an extension of Mira pulsation and a Mira period distribution curve is derived from the instability strip calculated in their model. The model also predicts a higher number of Miras than actually observed (Barket and Tuchman 1980), which can be attributed to the low luminosity limit that they calculate Mira pulsation would occur.

A common prediction of pulsational instability models is that finite amplitude pulsation in the fundamental mode is not possible and the subsequent relaxation oscillations will lead to PN ejection. The truncation of Mira period at $\sim 600^d$ in these models however, fails to account for the existence of long period ($P > 1000^d$) OH/IR sources in our Galaxy and supergiant variables in the SMC, which are almost certainly stable fundamental mode pulsators. IRC 10°216, which has a period of $\sim 650^d$ is also likely to be pulsating in the fundamental mode, yet its CO brightness distribution can be accurately fitted by a wind model to as far as 3' from the star (Knapp *et al.* 1982, Kwan and Linke 1982), suggesting a stable mass loss history of at least 14,000 yr. While an unstable pulsator in the TSB model also has a period of ~ 2 yr (Figure 12, TSB), the runaway ejections of ~ 50 yr separation are simply not observed in IRC 10°216. Even if such shell structures are smoothed by radiation pressure on grains and the resultant grain-gas interactions, the predicted ejection time scale of $\sim 10^3$ yr is too short to explain the extensive CS envelopes of most IR stars.

Furthermore, PN masses calculated by TSB ranges from 0.4 to 6 $M_\odot$, corresponding to progenitor stellar masses of 1-7 $M_\odot$ (see Figure 2 of Barket and Tuchman 1980). It is difficult to reconcile these predicted values to observed masses which lies in the range of 10^{-3}-0.3 $M_\odot$ (Pottasch 1980).

To summarize, although our intuition suggests an impulsive event as the cause of PN, there does not seem to exist adequate theoretical or observational evidence to support it. Envelope instabilities may still occur, but mass lost by a steady wind seems to dominate over any mass ejected over a short time interval. Any instability model however should at least adopt a proper outer boundary condition taking into account the existence of the CS envelope, as it is done in Wood (1979) and Willson and Hill (1979).

VI. PROTO-PLANETARY NEBULAE

The best candidate for a proto-PN (defined as a star in transit between AGB and PN) is probably GL 618 which has a central star of spectral type B surrounded by a CS envelope expanding at ∿20 km s^{-1} (Zuckerman 1978). A compact (∿0.2") ionized region is found at the stellar position and the CS envelope is likely to be ionization bounded (Kwok and Feldman 1981). Since its galactic location is in a incompatible with a pre-main-sequence object, its high luminosity ($3\times10^4[D/2\text{kpc}]^2\ L_\odot$) suggest that it is a proto-PN with a central star of ∿1 $M_\odot$. With ≳2 $M_\odot$ of wind material in the CS envelope, the main-sequence mass of GL 618 is probably >4 $M_\odot$. Shock-excited H_2 emission (as in NGC 7027) has been detected and this is likely to be due to the interaction of the nascent PN shell and the remant red-giant wind.

If GL 618 is indeed a proto-PN then its evolution could be relatively rapid (on a time scale of decades because of the high mass of the central star [Paczyński 1981]). This may offer us an unique opportunity to witness the birth of a PN and test many of our ideas on PN evolution.

VII. CONCLUSIONS

We suggest that AGB evolution is terminated not by a sudden ejection but by a steady wind over a period of >>10^4 yr. Since the precise mechanism responsible for the wind is unresolved, a detailed picture of the transition to PN is still lacking. What is certain, however, is that stellar winds from both red giants and PN-nuclei play significant roles in the formation and evolution of PN. Although a complete understanding of the morphology of PN may involve other complicating factors not described in this paper, it is expected that the interacting winds process will remain a basic component of the PN phenomenon.

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ROXBURGH: There is evidence from the rotation rates of solar-type stars for a sudden change in angular momentum and mass loss rates. I recently produced an explanation of this phenomenon which can be extended to Red Giants: the mass loss is controlled by dynamo-generated magnetic fields and, as the star slows down, the dynamo switches to a different order mode, allowing a sudden change in mass loss rate.

KWOK: I have so far avoided discussion of mass loss mechanisms. Such mechanisms have been suggested (e.g. Wood, 1979, Astrophys. J. 227, 220; Willson and Hill, 1979, Astrophys. J. 228, 854) that could lead to an increase in the mass loss rate and be responsible for the observed increase in wind strength near the top of the AGB. However, present observations do not support the idea that a sudden (10^3y), large mass loss is responsible for the formation of a PN.

BESSELL: The relative number of radio luminous OH/IR sources to Miras (1 : 60) suggests that the lifetime of a OH/IR source is about 10^4y. To dissipate the large envelope in this time, a very high mass loss rate is required. The long periods of many of these sources ($\approx$ 1000 d) suggest that they pulsate in the fundamental model, which is unstable, leading to relaxation oscillations and shock ejection. The sharp long period edge to the luminosity-period relation for Miras in the Magellanic Clouds shows that something special happens at these periods. It is reasonable to connect these facts and draw the conclusion that envelope ejection in Miras does not occur over a long time at a high rate of mass loss, but that the switch in pulsation mode from first overtone to fundamental results in rapid mass loss and a short time as a OH/IR source before becoming a PN.

KWOK: Since the very long period variables are likely to originate from high mass ($> 2M_\odot$) stars, it is not surprising to find fewer of them in view of initial mass function and their rapid evolution. In any case, the dynamical time (R/v) of many IR stars greatly exceeds the ejection time scale ($\lesssim 10^3$y) predicted by sudden ejection models. I agree, however, that pulsational mode switching can lead to an increase in the mass loss rate during the later part of the AGB evolution, as suggested by the mass loss formula used in my Fig. 1.

TERZIAN: We have heard suggestions that the PN mass (ionized and neutral gas) can be very large, up to a few $M_\odot$. Does this contradict your model?

KWOK: Halos of PN can be explained, in the interacting winds model, as remnants of the Red Giant wind. As can be seen from my Fig. 1, the halo mass may be as high as several $M_\odot$.