EFFECTS OF MASS LOSS ON THE FORMATION OF PLANETARY NEBULAE

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The idea that planetary nebulae (PN) originated from outer layers of red giants goes back to Shlovskii (1956). This hypothesis was supported by Abell and Goldreich (1966) who argued convincingly that red giants are the most likely progenitors of PN. Although this is generally accepted today, the details of the transition from red giants to PN remain in controversy. It was pointed out by Paczyński (1971 a) that PN progenitors must have similar luminosities to central stars of PN, and therefore are likely to be late-type supergiants undergoing double-shell burning. The advent of infrared astronomy led to the discovery that most, if not all, late-type giants and supergiants are losing mass at rates of 10^{-6} - 10^{-5} $M_\odot yr^{-1}$ (Gehrz and Woolf 1971). Such mass loss rates greatly exceed the nuclear burning rate (6 x 10^{-8} - 5 x 10^{-7} $M_\odot yr^{-1}$ for stars with core masses between 0.6 and 1.2 $M_\odot$) and must be the dominant factor in the late evolution of intermediate mass stars. The observation of white dwarfs in open clusters implies that up to 6 $M_\odot$ can be lost during the red-giant phase (Romanishin and Angel 1980). Since the observed masses of PN are no more than a few tenths of a solar mass, the existence of massive circumstellar envelopes formed by steady mass loss must have an effect on the formation of PN.

It has long been known that a star with core mass between 0.6 and 1.2 $M_\odot$ will remain with spectral type later than K0 if the envelope mass is above $\sim 10^{-3}$ $M_\odot$ (Paczyński 1971 a). This implies that even if there is no mass loss in stars blueward of spectral-type K0, the movement toward the PN nucleus state is very rapid. In this case, one would find a hot star inside a diffuse envelope of considerable mass. It might be asked whether the remnant of the red-giant envelope, when ionized by the hot core, could be observed as a PN (Paczyński 1971 b). However, there exists several pieces of observational evidence against such a suggestion:

1. The observed expansion velocities of PN (20-50 km s^{-1}) are higher than the stellar wind velocities from asymptotic giant branch (AGB) stars (3-20 km s^{-1})
2. The observed densities of PN are higher than the expected densities in the remnants of red-giant envelopes.
3. Many PN have well-defined shell-like structures whereas red-giant envelopes do not.

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It is clear that although red-giant winds play an important role in the formation of PN, they cannot alone be responsible. Instead, according to Kwok, Purton and FitzGerald (1978), continuous mass loss gradually removes the hydrogen atmosphere of a red giant, and together with nuclear burning, eventually exposes the hot core. The change in the effective temperature of the star, from 2000-3000 to 30000-100000 K, then leads to a change in the mass loss mechanism (probably to radiation pressure on ionized gas), resulting in a 100-fold increase in ejection velocity. This new wind will act like a snow plow and will build up a high density shell at the surface of collision. The shell will be pushed by the central-star wind and retarded by the old red-giant wind, quickly reaching an equilibrium expansion velocity. The mass of the shell will increase as more material in the old wind is being swept up by the shell. Over a period of several thousand years, the shell will have all the observed properties of a PN.

Compared to other models of PN formation, this model has several attractive features:

1. It makes no assumption about physical processes which have not already been observed. AGB stars are known to have winds with velocities from 3-25 km s^{-1} and mass loss rates of 10^{-6} - 10^{-5} $M_{\odot} yr^{-1}$. Fast ($v \sim 2000$ km s^{-1}) winds from central stars of PN have also been detected by recent IUE observations.

2. Since the shell is dynamically constrained by two winds, the model easily explains the sharp outer and inner edges observed in PN shells. The dilemma of backfill is also avoided (Mathews 1966).

3. There exists observational evidence for the presence of remnant red-giant envelopes outside PN shells (*cf* Kwok 1981).

4. The model predicts that the mass of the shell increases with the nebular size. Such a correlation has been found by Pottasch (1980).

From the stellar evolution standpoint, this model does not require a major modification of the evolutionary scenario proposed by Wood and Cahn (1977). In their picture, PN are formed either by 1) low mass Mira variables in which the entire nebula has been created by mass loss; or 2) high mass Miras which have undergone sudden envelope ejections. Our model suggests that low mass Miras need a fast wind in order to develop an observable PN shell. Also, all Miras will probably develop higher mass loss rates while ascending the AGB, possibly due to radiation pressure on grains enhanced by shocks (Wood 1979). Observed mass loss rates from oxygen-rich OH/IR stars or carbon-rich CO/IR stars often exceed 10^{-5} $M_{\odot} yr^{-1}$ (Zuckerman 1980). These rates are 100 times higher than the mass loss rates assumed by Wood and Cahn and are probably capable of completely removing the hydrogen envelope before the core reaches the Chandrasekhar limit. A separate ejection is therefore not necessary. Even if sudden ejections do occur, the ejected shell will sweep up matter from the remnant red-giant envelope, and the PN shell will be at least in part made up of wind material.

One should note however, that the only mass loss process relevant to the formation of PN is during the immediately preceding 10^4 years. It is well known that Pop. II stars rarely ascend above the first giant branch and it is quite probable they never develop the high mass loss rates observed in OH/IR stars. As a matter of fact there exists little direct evidence that Pop. II stars are actually losing mass. The amount of mass loss required to produce the horizontal branch can occur at very low rates. It also takes place at the first giant branch which is not connected to the PN phase. Therefore, it would not be surprising to find the proportion of PN to be different in Pop. I and Pop. II systems.

In fact, PN are known to be numerically under-abundant in the galactic halo (Alloin *et al.* 1976). It has been suggested that PN are predominantly metal-rich objects (Barker 1978, Aller and Czyzak 1979). The galactic distribution of PN indicates that they can be classified as intermediate Pop. I, suggesting that their progenitors have main-sequence masses between 1.5-3 $M_\odot$.

The present rate of mass return to the interstellar medium from PN ($\sim 1.5 \times 10^{-10}$ $M_\odot pc^{-2}$ yr^{-1} Alloin *et al.* 1976) is similar to, but slightly less than, that from late-type stars ($\sim 6 \times 10^{-10}$ $M_\odot pc^{-2}$ yr^{-1}, Osterbrook 1974), although the calculated rates are based on quite separate observational grounds. Such a coincidence is not unexpected in our model of PN formation because the PN phenomenon does not represent a separete ejection of matter but just a reorganization of matter ejected during an earlier epoch. In other words, the PN phenomenon is only a different manifestation of the mass-loss process.

In summary, AGB stars eject a significant amount of mass in the form of a stellar wind just prior to the PN phase and such matter must have an effect on the formation of PN. The fast winds developed by central stars of PN may also contribute sufficient momentum to be dynamically important in the evolution of PN.

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DISCUSSION

RENZINI: How do you explain the PN in the globular cluster M15?

KWOK: I think it is interesting already that there is only one PN in all globular cluster. Since one would expect more if globular clusters have the same NPN/Mass ratio as the galaxy. Furthermore, the mass of the PN in M15 according to Peimbert, is low compared to the average mass of PN. I do not claim that there is no PN in Pop II systems, only that they are likely to be of lower mass and/or fewer is number.

FEHRENBACH: Comment expliquez vous que dans la nebuleuse anulaire de la Lyre l'image en He II (4685) est beaucoup plus petite que l'image en $H_\alpha$ou dans d'autres raies ([O III] etc.). L'anneau n'a donc pas une limite nette interieure et probablement pas exterieure.

KWOK: The fact that the photograph shows a ring structure indicates that the major of the nebula mass is dynamically confined. The interacting -stellar- winds model does not predict a complete vacuum in the central region, only lower density. High excitation lines may be observed there. There are many different morphologies of PN and clearly no one model can explain them all.

PANAGIA: In your scheme the mass of a planetary nebula envelope increases linearly with time. As a consequence, the volume emission measure, hence the radiation flux, in the optically thin phase is expected to vary like t^{-2} instead of t^{-3} as in the case of constant mass. This has effect of increasing the time over which an optically thin PN can be detected and, therefore, of raising the fraction of optically PN's relative to the total (optically thick & optically thin PN's). Has this aspect been checked against observational data?

KWOK: Our model predicts that $M_S \propto t$, $N_e \propto t^{-2}$, $R \propto t$, and $\Delta R/R$ = constant. Observationally, the relevant parameter is N_e^2V, which is our model is proportional to t^{-1}. In the constant mass ejection model, assuming total diffusion, the $N_e^2V \propto t^{-3}$. For example, if we compare a constant mass nebula of mass 0.3 $M_\odot$ with velocity 40 km/s to a nebula with M_s (10^4 yrs) = 0.3 $M_\odot$ under the hypotheses of our model, we find that $N_e^2V = 4.2 \times 10^{58} (10^4 \text{ yrs} / t)^3$ and $N_e^2V \simeq 4.5 \times 10^{58} (10^4 \text{ yrs} / t)$, respectively . Although the optically thick phase if longer in the constant mass ejection model, the total observable lifetimes do not differ greatly.

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NUSSBAUMER: Pottasch has found a correlation between planetary nebula shell mass and age of the nebula in the sense that younger nebulae have lower masses. Low masses need not necessary mean low masses of the total nebula. It could simply mean a small ionized region. Nussbaumer and Schild when interpreting the spectrum of the symbiotic star in terms of a planetary nebula model find for the H^+ nebula M = = 10^{-4} $M_\odot$ only. But this H^+ region is ionization bounded. From C II and Si II lines we have evidence that the H^+ region is surrounded by a H^O region.

PANAGIA: To the best of my knowledge, most, if not all, of the planetary nebulae considered by Pottasch are ionization bounded and, therefore, the correlation between nebular mass and age is not conclusive evidence in favour of a genuine increase of the mass with time. A similar analysis should be repeated for a sample of optically thin PNs with well determined distances.

KWOK: Pottasch found the masses of PN range over a factor of 500; it is unlikely that they are all ionization bounded. In any case, this can be easily checked by calculating the size of the Stromgren sphere. Since the electron density (not mass) is the observed quantity, it would be interesting to compare the correlation between N_e and R found by Pottasch with the prediction of the model.

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