PLANETARY NEBULAE FORMATION

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It is a well accepted idea that Planetary Nebulae (P.N.) formation is due to mass ejection from red giant envelopes.

According to the original model, as was proposed by Roxburgh and Lucy in 1967, and established about a year later by Paczynski and Ziolkowski (1968), red giant envelopes become dynamically unstable above a certain boundary luminosity, while their total energy, including the ionization energy, which should be available upon expansion, is positive. This energy is sufficient for ejecting the entire envelope with a velocity similar to those observed in P.N.

In the light of these facts, it was quite natural to look for "one shot" ejection mechanisms in unstable red giant envelopes, using full non-adiabatic dynamical codes. This has been done several times since the adiabatic analysis carried out by Paczynski and Ziolkowski (1968), but with minor success, at least in those cases where natural initial conditions were used.

It was found that as soon as the radial expansion of the envelope becomes comparable to its initial radius, the entire radiative zone, which is located above the partial ionization zone, turns to be almost completely transparent. Thus, most of the released recombination energy is radiated directly out of the star, instead of pushing mass shells outwards. Since this energy leakage is very fast, motion is quickly reversed without resulting in any mass loss. Nevertheless, it was pointed out by Smith and Rose (1972) and later by Wood (1974) that there is a possibility for some mass ejection due to shocks generated within the contracting envelope.

We will show that this shock ejection mechanism is repetitive in a semi-regular way with a short time scale ($\lesssim$30 yr) and, as far as P.N. formation is concerned, the entire envelope is ejected in less than 1000 years, leaving less than .001 $M_\odot$ of the original envelope above the core. We shall start with a general description of the dynamical adventures of red giant envelopes at the relevant evolutionary stage,

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namely, the Asymptotic Giant Branch. A huge number of red giant envelopes that satisfy the well-known core mass / luminosity relationship were integrated. The main results concerning their dynamical character are summarized in Figure 1.

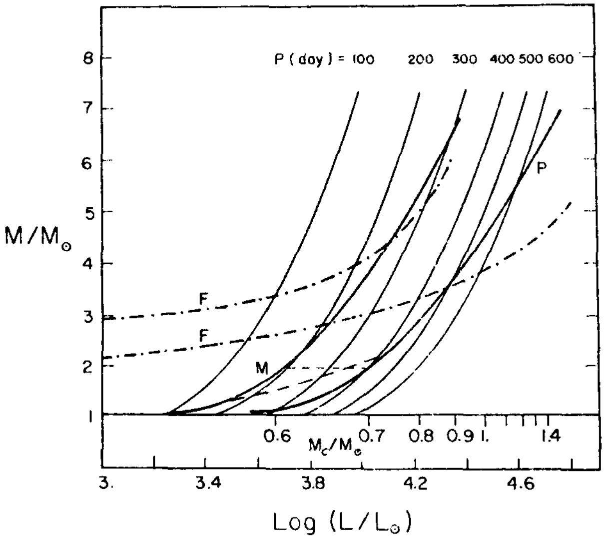

Figure 1

Given on the $M - M_c$ (or logL) plane are : equi-period lines (light full lines) labelled by their respective periods (in days); heavy full lines describe the M and P lines (see text).

Most of the envelopes which are located to the left of the "M-line", where M stands for Mira, are completely stable, but even those which are pulsationally unstable are oscillating with an amplitude too small and irregular to be identified as Mira stars.

Beyond the M-line, at higher luminosities, envelopes are pulsating steadily in their first overtone (Fig.2). Their periods, as well as other observable features, are in very good agreement with those of Mira stars. As the envelope luminosity is further increased, approaching the "P-line", the fundamental mode begins to show up and the envelope is oscillating in a mixture of the two first modes (Fig. 2). At the P-line, the fundamental mode dominates and a steady state is not achieved any more; rather, pulsation begins to diverge (Fig.2), followed immediately by a mass-loss process.

It should be emphasised that this mass-ejection mechanism, which is a result of pulsational divergence, occurs before dynamical instability is reached. An important consequence of this fact is an extension of the traditional mass range for P.N. formation, by increasing its upper limit from about 4 $M_\odot$ to at least 7 $M_\odot$ (Tuchman, Sack and Barkat 1978). This causes, on the other hand, a drastic reduction in the mass range for the carbon-detonation phenomenon.

As an example of the ejection process we shall follow the dynamical evolution of a 1 $M_\odot$ star from the point where its pulsation begins to diverge (Fig.2c). With a complete resemblance to the case of dynamical instability, the expanding envelope loses an appreciable fraction of its stored ionization energy, expansion ceases, and the following contraction

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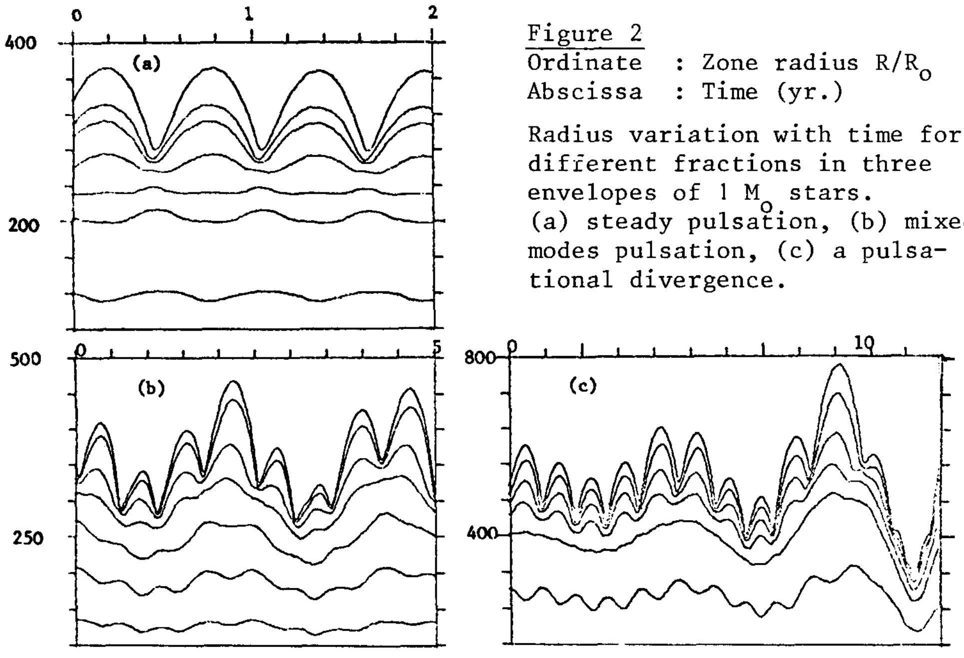

Figure 2
Ordinate : Zone radius R/R_o
Abscissa : Time (yr.)

Radius variation with time for different fractions in three envelopes of 1 M_o stars.
(a) steady pulsation, (b) mixed modes pulsation, (c) a pulsational divergence.

turns quickly into a fast collapse (Fig.3).

Note that those mass shells where recombination has occurred during expansion will have, due to re-ionization, a "soft" equation of state, and thus they will acquire relatively high infall velocity, while inner zones, which hardly participate in the expansion, will behave as a rather stationary wall with respect to the infalling outer zones. A hard bounce

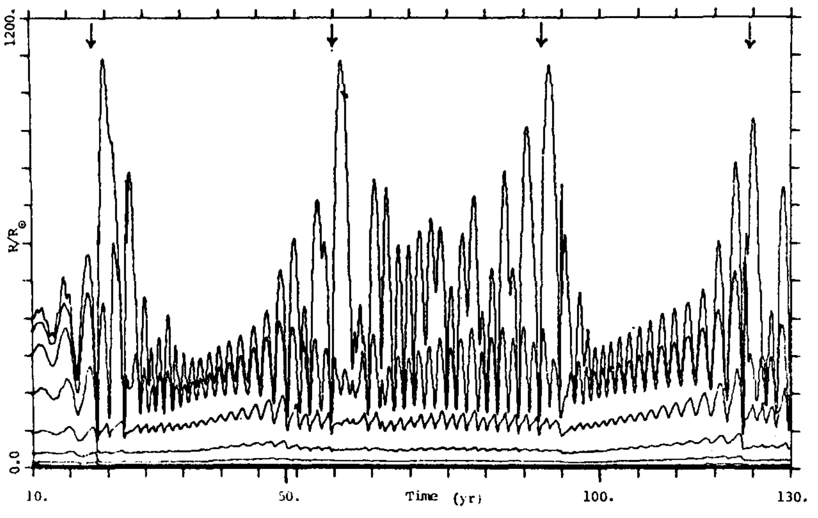

Figure 3. Radius variation with time for different mass fractions in a model ejecting mass (arrows indicate where ejections occur).

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occurs and a reflected shock is generated. Travelling outwards, this shock becomes even stronger passing through less dense layers. Eventually, a significant fraction of the initially radiative zone, about 3% of the entire envelope, attains the escape velocity and is ejected.

The remaining matter reverses its motion and continues to oscillate moderately. Since, at this stage, the ingoing luminosity is much higher than the surface luminosity, the star increases its internal energy content. On reaching its original (static) level, roughly, a new cycle expansion-collapse-ejection occurs. The time interval between successive ejections is thus the time required for the internal energy reconstruction, which can be roughly estimated as: $\Delta t \cong \alpha . 6\times10^5 . (M/M_\odot)/(L/L_\odot)$ (yr.)

α, which is the fraction of the ionization energy reservoir lost in the expansion phase, turns out to be around 0.3, while the ratio of the envelope mass to its luminosity is about 10^{-4} for the initial models. Thus the time interval is close to 25 years at the beginning of the mass loss process and it is decreasing together with the envelope's mass reduction.

The dynamical behaviour of the envelope, as can be seen from Fig. 3, is convincingly displaying a semi-regular character for this process.

The obvious way to find out to what extent mass loss occurs is to continue these calculations. It is however quite costly and can be easily avoided. We construct new envelopes in thermodynamic equilibrium with the same luminosity and core mass but with an arbitrarily reduced envelope mass. The same mass loss process was quickly developed in all these models. In particular, mass ejection was found even in an envelope with a total mass less than $10^{-3}M_\odot$, inconsistent with the theory of P.N. nuclei evolution. Finally, using the formula above for Δt, the time interval between successive ejections, together with the assumption, justified by calculations, that at each ejection about 3% of the prevailing envelope is lost, the period of time required for ejecting the entire envelope turns out to be close to 1000 years.

In conclusion, the extreme non-adiabatic behaviour of red giant envelopes which prevents their ejection in "one shot" mechanisms, turns out to be the main cause for multiple ejection.

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