EVOLUTION OF UNSTABLE RED GIANT ENVELOPES

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Two main observable phenomena are directly connected with the dynamical behaviour of Red Giant (R.G.) envelopes: The variability of Mira stars and Planetary Nebulae (P.N.) ejection.

According to our dynamical research in R.G. envelopes it turns out that a repetitive shock ejection, which we propose as the mechanism for P.N. formation, is practically the final stage of the Mira phase. Therefore these two phenomena are closely related to each other and should be simultaneously discussed.

Since the characteristical evolutionary time of R.G. stars is much longer than any relevant time typical of their envelopes, the strategy beyond our dynamical calculations was the following: Static models of R.G. envelopes were integrated along their evolutionary track, using the well known luminosity - core mass relationship and assuming a perfect thermodynamical equilibrium.

The dynamical features of these envelopes have been examined by tracing the nonadiabatic thermodynamical variations which are excited in the envelope due to a small radial perturbation. Each dynamical calculation was continued until one of the following situations was reached:

1. The perturbation dies out and the envelope returns to its initial static position.
2. A steady pulsation is clearly established (see fig. 2).
3. A fast mass loss process begins. (see fig. 4).

It turns out that each R.G. passes along its evolution on the Asymptotic branch, all three possibilities in the order listed above. This fact is clearly demonstrated in the following figure: (fig. 1).

D. R. Flower (ed.), Planetary Nebulae, 281–289.

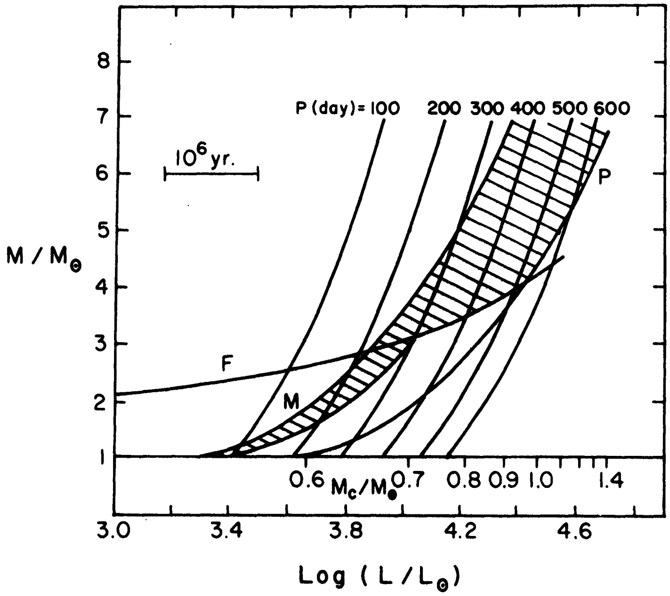


Fig. 1 - Given on the M-M_c (or log L) plane are: equiperiod lines labeled by their respective periods (in days). M,P and F lines (see text). Dashed area is the trucated Mira strip. The segment on the upper left corresponds to an evolutionary time interval of 10^6 years.

Envelopes located to the left of the "M line" are pulsationally stable or are oscillating with an amplitude too small and irregular to be identified as Mira stars. Most of these stars are oscillating in modes higher than the first.

Beyond the "M line" (Fig. 1), at higher luminosities, the envelope is oscillating steadily in the first overtone (Fig. 2). Their periods as well as many other observable features are, as we shall show later, in a good agreement with those observed in Mira variables.

Approaching the "P line" (Fig. 1) the fundamental mode begins to show up, and the envelope oscillates in a mixture of these two modes (Fig. 3). Crossing the "P line" the fundamental mode dominates the pulsation diverges and mass loss process is initiated (Fig. 4).

I will not go into the details of the ejection mechanism since it has been widely described more than two years ago (Tuchman et al 1979.). Briefly, the mass loss process is based upon repetitive shock ejections where the star is losing about 3% out of its prevailing envelope per ejection. The time interval between successive ejections, which is practically the envelope's thermal time scale, is about 30 years. The typical time for losing the entire envelope is therefore about 1000 years.

Fig. 3 (see below) Radius variation with time for different mass fractions of a mixed mode variable.

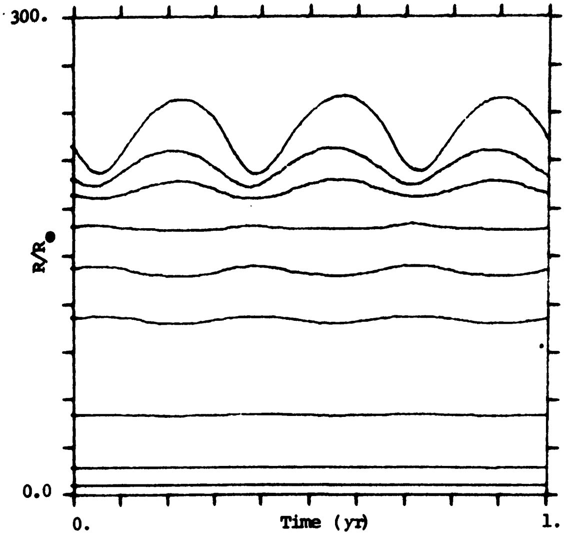
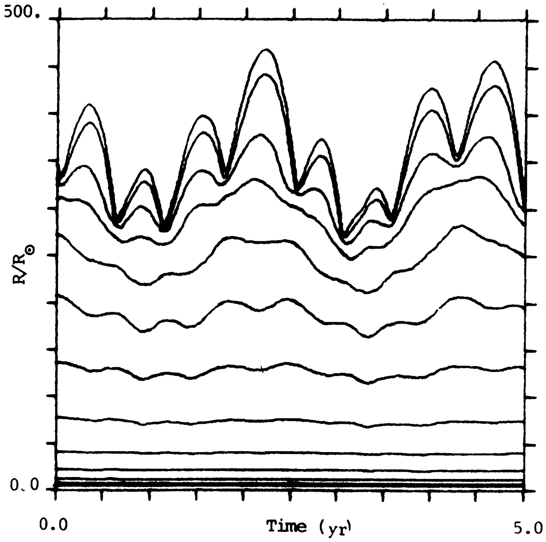


Fig. 2 - Radius variation with time for different mass fractions of a steady first overtone Mira.



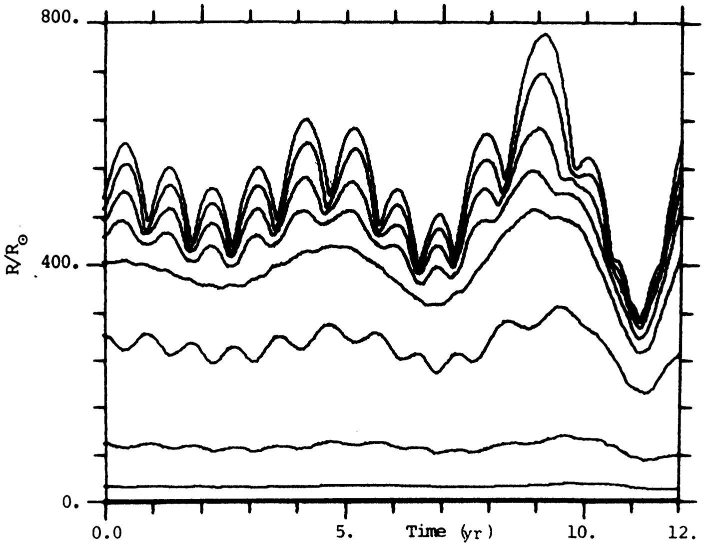


Fig. 4 - Radius variation with time for different mass fractions of a star at a stage of pulsational divergence.

The agreement of this dynamical picture with observation can and should be examined with respect to the following issues:

a) The Mira stage; where we should compare with observation not only the properties of diffarent variables as singles, but also some important statistical correlations which are observed among them.

b) The ejection process; where we should look for possible influence of the ejection mechanism upon the observed structure of the nebulae.

c) The remnant compact nuclei, mainly their expected and observed mass distributions.

What can be deduced from the specific shape of the Mira strip (Fig. 1)?

First, according to the given equiperiod lines, Mira periods should range from 100 to 600 days, where the surface luminosity and the total mass are, on the average, increasing functions of the period. This is precisely the observed situation (Eggen 1975).

Second, according to Fig. 1, stars oscillating with periods longer than 200 days should have total mass above $1.1M_\odot$. This fact might be an explanation for the absence of these stars, with periods higher than 200 days, in globular clusters (Feast 1972).

Another well known correlation, observed among the Mira variables, is concerned with their luminosity profile. In Fig. 5 the luminosity rise time divided by the total period (≡f) is shown as a function of the period for a sample of Miras presented by Campbell (1955).

According to our dynamical calculations a star with a given mass evolves within the Mira strip from a symmetric light curve ($f \stackrel{\sim}{\sim} 0.5$) to a light curve with a sharp increase towards the maximum and a moderate decline afterwards ($f \lesssim 0.3$). Since Mira stars having short periods naturally happen to exist at the beginning of the strip (Fig. 1) and those with long periods are found mostly close to the end of it (Fig. 1), one should expect precisely the observed correlation as is described in Fig. 5.

Let us pass to the major discrepancies between the presented theoretical picture and the observed data;

Using the time width of the Mira strip together with the theoretical death rate of main sequence stars (Chan and Wyatt 1976) one can predict the expected number distribution of Mira variables as a function of their periods. Such a calculated distribution is shown in Fig. 6.

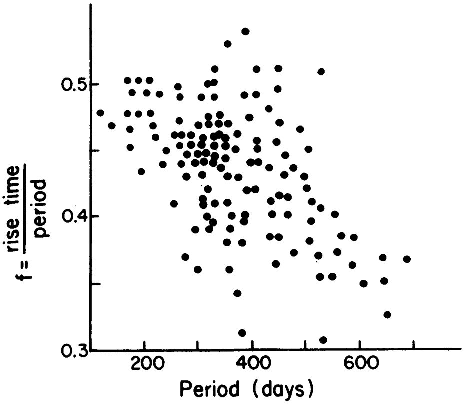


Fig. 5. - Luminosity rise time divided by the total period (f) as a function of period for a sample of Miras (Campbell (1955)).

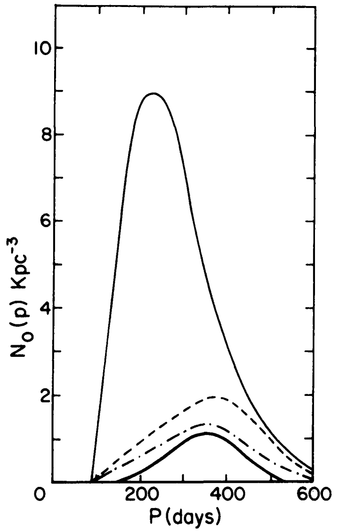


Fig. 6. - Number density N⊙ (Kpc^{-3}) of Miras as a function of period for no steady mass loss and no truncation (solid light line), truncation without steady mass loss (dashed line), truncation with steady mass loss (dot-dashed line) & observed curve (solid heavy line).

The observed distribution as has been prepared by Wood and Cahn (1977) is shown as well (Fig. 6). The discrepancy is obvious and significant First, in the general shape of these curves, where the observed distribution has its maximum near 350 days and has a sharp decrease both towards 100 and 600 days, while our calculated distribution has a peak near 200 days and quite a moderate decline towards the lower periods. Second, and more serious, is the clear disagreement in the total integrated number density, proportional to the area enclosed beneath these curves. According to Wood and Cahn (1977) the observed local number density of Mira variables is 245 per Kpc, while our predicted number ($\sim$1500 per Kpc) is about six times larger.

These two discrepancies can simultaneously be removed if, for some reason, the lifetime of low mass Miras is drastically diminished, which means a truncation in the lower right part of the Mira strip (Fig. 1).

A natural reason for this truncation is provided by the theoretical well known double shell flashes which are believed to occur in the relevant evolutionary stage. If, during such a flash, the surface luminosity exceeds the quiet value, then, there is a possibility for a R.G. to be removed from its position, some where in the Mira strip, to the other side of the "P line" initiating a mass loss process.

In order to carry out a qualitative analysis of this theoretical possibility, one should have the following needed information:

a) The location in the mass luminosity plane, where double shell flashes first occur. (will be denoted "F line")

b) The time dependent luminosity

profile during the flash mainly the height of the luminosity peak and the time interval during which the luminosity exceeds the critical value for mass ejection (The corresponding value at the "P line").

An approximated "F line" that has been compiled from various published results is shown in Fig. 1. Unfortunately, its location is quite uncertain, since it is sensitive to physical and numerical factors, which are far from being clear. In any case it is safe to assume that double shell helium flashes start before the Mira phase at least for stars less massive than $2M_\odot$.

The knowledge concerned with the second point has been for a long time a vague issue as the results found by various authors in literature showed huge discrepancies. Lately, an article devoted precisely to clarifying this point has been published by Wood and Zarro (1981). Using their results, which we believe to be the most reliable at the present time, the Mira strip is truncated in a way shown in Fig. 1. Note that this truncation, which turns out to be independent of the star's total mass, exists only across (to the right) of the "F line".

The number distribution of Mira variables, recalculated for the truncated Mira strip, seems to be much closer to the observed one (Fig. 6), and if the influence of Reimers - type steady mass loss is also added, which means that the star's mass is reduced while evolving through the Mira stage, then the agreement with the observed curve becomes even better.

Having some more confidence with the results concerned with the Mira phase, we may proceed to the next point; The ejection process.

As has been already mentioned earlier, the typical time scale for losing the entire envelope, according to our proposed ejection mechanism, is close to 1000 years, which means a mass loss rate of about $10^{-3} M_\odot$/yr. Using this value and the observed expansion velocities of the nebula (20-50 Km/sec), one can easily obtain the density and the nebular width as a function of the radial distance from the remnant nucleus (for a given mass of the nebula). As an example, for a nebula of $0.1M_\odot$ at a radius of 0.1 Pc the expected density is about 10^4 particles per cubic cm. and the nebular width is about a tenth of its radius. These values are very close to the observed ones.

According to the described dynamical situation there is a high probability for P.N. formation stimulated by helium shell flashes. An obvious question to be asked is whether there is any evidence for this fact in P.N. observational data.

Let us assume that the nebula ejection is indeed initiated by a luminosity peak associated with a helium shell flash. Since the time interval needed for this created nebula to be observed is much longer than the time width of the luminosity peak, there is no chance to observe luminosity variations, corresponding to this helium flash, in the remnant nuclei. On the other hand, since the time width of the luminosity peak is similar to or shorter than the estimated time interval for the nebula creation ($\sim$1000 yr.), it is quite reasonable to assume that in some cases the mass ejection will cease before the entire envelope is lost. The rest of the envelope, in these cases, will probably be ejected only during the next flash. This might be the mechanism for double shell P.N. formation in which the spatial interval between the shells corresponds to the time interval between successive flashes.

The detailed calculations needed to find out whether a certain star will or will not create a multiple shell P.N. is far from being simple. This is mainly due to the fact that the critical value for mass ejection (at the "P line") changes simultaneously with the decrease of the total mass. Thus let me point out the main results:

a) Stars with total mass close to $3M_\odot$ are the expected candidates for double shell P.N. formation. Note that the interflash period in these stars is about 10,000 years (Paczynski (1975)).

b) The calculated statistical occurrence of multiple shell P.N. approach 15%.

These conclusions are compatible with observational evaluations. (Kaler (1974)).

Finally, let us pass to the last stage. The remnant nucleus.

Lately huge progress has been made in analysing the observational data concerned with the evolution of P.N. nuclei. This has been done mainly by Wiedeman and Schonberner (separately (1981), and together (1981)).

According to their investigations the mass distribution of P.N. nuclei is sharp and narrow, concentrated around $0.58M_\odot$.

Our predicted P.N. nuclei mass distribution, based upon the location of the corrected "P line" (Fig. 1) and the mass dependent death rate of Main Sequence stars shows an excellent agreement with observation (Fig. 7).

Just for comparison we show also the distribution one should get by assuming a continuous Reimers-type mass loss as the only mechanism for the nebula ejection (Fig. 7). (assuming η=1).

This distribution which is identical with the distribution of masses for bright W.D. can be integrated to the past, using a time dependent stellar birthrate function, to get a distribution for all W.D. masses. This distribution turns out to correspond quite well with the observational estimates (Weideman 1980).

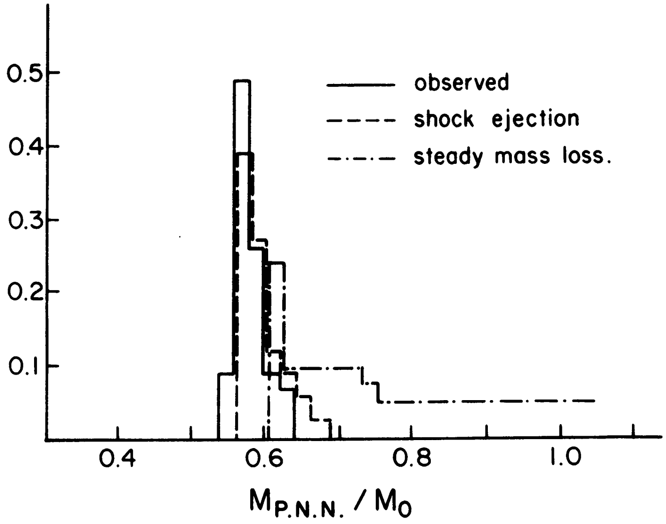


Fig. 7. - Mass distribution of Planetary Nebula nuclei ($M_{P.N.N.}$) calculated from our theoretical model (dashed line). The observed curve (Wiedeman and Schonberner (1981)) (full line). The distribution one should get assuming a continuous Reimers type mass loss is given as well (dot-dashed line).

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WANNIER: I was particularly intrigued by the approximate 30 y interval between mass ejections, especially in the light of the similar interval between different velocity components in several mass-loss objects. What is the fundamental cause of this extended periodicity?

TUCHMAN: Since each ejection is the result of a huge expansion during which the envelope loses a major part of its thermal energy, the time interval of about 30 y is needed to reconstitute the internal energy of the envelope and is close to the envelope's thermal time-scale.

RENZINI: While the qualitative behaviour of your models is of great interest for the understanding of the superwind, all the quantitative aspects should be viewed with caution. In particular, derived Mira period distributions depend crucially on the relation adopted between effective temperature, luminosity and mass of AGB models and on the treatment of superadiabatic, time dependent convection.

KALER: With the latest data, the mass distribution of planetaries is wider than the one which you presented. This issue is far from being settled.