THERMAL PULSES AND PLANETARY NEBULA EJECTION

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ABSTRACT. Thermal pulses in AGB stars cause large luminosity variations at the stellar surface. The role of these luminosity variations in the production of planetary nebulae is discussed. Results of theoretical evolution calculations which include mass loss modulated by thermal pulses are presented.

1. Thermal pulses and AGB evolution

The hydrogen and helium burning shells of AGB stars do not burn smoothly. For most of the time, the hydrogen burning shell is active while the helium burning shell is essentially dormant. Periodically, at intervals of typically $5x10^4$ - 10^5 years for low mass stars, the helium shell ignites violently and burns up the helium produced by the hydrogen shell since the last phase of helium shell activity. Then, when the inter-shell helium supply is exhausted, helium shell burning dies out and hydrogen burning recommences. These periodic bursts of activity by the helium shell, first discovered by Schwarzschild and Harm (1965), are called *helium shell flashes* or *thermal pulses*. In the present context, their most important effect is to modulate the luminosity appearing at the surface of the star: a typical example of thermal pulse behaviour is shown in Figure 1. Two important features

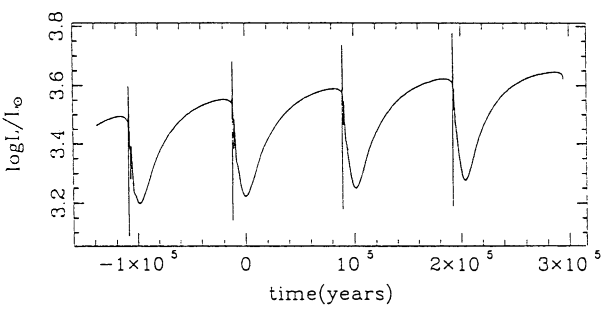

Figure 1. The time dependence of the luminosity in a thermally pulsing AGB star with a core mass $M_{core} = 0.58\ M_{\odot}$ and total initial mass 1.0 $M_{\odot}$.

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should be noted in these light curves. Firstly, there is a brief spike of luminosity which lasts ~500 years (Wood and Zarro 1981; Boothroyd and Sackmann 1988) and which is a direct result of the escape of energy released by the initial burst of helium burning. In low mass stars, the peak of this luminosity spike is typically 50% higher than the maximum luminosity during hydrogen burning. Secondly, there is a slow variation of luminosity by a factor of ~2 throughout the whole shell flash cycle: the initial decline to luminosity minimum coincides with the phase of helium shell burning while the recovery to luminosity maximum corresponds to the phase of hydrogen burning. Note that the long-term increase in average luminosity resulting from the increase in the core mass is dominated by the luminosity variations resulting from shell flashes.

2. Ejection mechanisms

Mechanisms invoked for the ejection of planetary nebulae (PNe) from single stars generally involve some instability of the envelope, and theoretical studies indicate that this instability is greater the greater the luminosity of the star. It therefore seems that thermal pulses and the surface luminosity variations that they produce will influence planetary nebula ejection.

One of the earliest mechanisms suggested for ejecting PNe was the dynamical instability of the envelope (Roxburgh 1967; Paczynski and Ziolkowski 1968). Roxburgh showed that as a star evolved up the giant branch, it would eventually become luminous enough that the fundamental pulsation mode eigenvalue σ^2 would become negative, giving rise to an unstable, exponentially growing expansion of the envelope. Paczynski and Ziolkowski (1968) also showed that in AGB stars the total envelope energy could indeed be positive so that once the envelope started to expand in the unstable mode it would have enough energy to escape to infinity. Many subsequent non-linear studies of this possibility (ex. Smith and Rose 1972; Wood 1974; Tuchman, Sack and Barkat 1979) indicated that AGB stars did not eject their envelopes via dynamical instabilities but instead underwent violent, irregular pulsation in the fundamental mode and suffered large amounts of mass loss. These results led Wood and Cahn (1977) to suggest that a the switch in pulsation mode of Mira variables from first overtone to fundamental mode that led to planetary nebula ejection by this process. However, recent observational and theoretical studies of Mira variables suggest that these stars are already steadily pulsating in the fundamental mode (Willson 1982; Wood 1990), so that both the non-linear pulsation studies exhibiting violent pulsation and the mode switch suggestion of Wood and Cahn (1977) must be incorrect (but see Tuchman 1991). It now seems that mass loss in AGB stars is produced by the joint action of steady pulsation and radiation pressure on grains (Wood 1979; Bowen 1988).

One other mass loss mechanism that may apply for more massive AGB stars is radiation pressure ejection of the envelope (Wood and Faulkner 1986). In this mechanism, if the luminosity at a helium shell flash exceeds the Eddington luminosity $L_{Ed} = 4\pi cGM_{core}/\kappa$ at the edge of the core (where the opacity is mainly due to electron scattering), then no hydrostatic solution for the envelope exists and the likely result is envelope ejection. Wood and Faulkner (1986) show that the condition $L > L_{Ed}$ occurs at the peak of a luminosity spike in AGB stars with core mass $\gtrsim 0.9\ M_\odot$ but with envelope mass $\lesssim 1.5\ M_\odot$. Since core masses $\gtrsim 0.9\ M_\odot$ are only likely to develope in AGB stars with mass $\gtrsim 5\ M_\odot$, and the initial envelope mass will then be ~4 $M_\odot$, the radiation pressure ejection mechanism could only work to remove the last ~1.5 $M_\odot$ of envelope material. It should also be noted that in the ~500 year duration of the luminosity spike, the total momentum of radiation emitted from the central core would be insufficient to eject this much envelope material (M. Morris, private communication). However, the total internal energy of these very luminous envelopes is often positive (Paczynski and Ziolkowski 1968), so that radiation pressure combined with gas pressure forces may be sufficient to eject a large amount of material.

3. When does planetary nebula ejection occur

The possibility that the luminosity spikes produced by helium shell flashes cause planetary nebula ejection is now examined. The two Mira variables R Hya and R Aql are currently in the luminosity spike phase of AGB evolution. These two variables have undergone period changes over the last century or two that are so rapid that they can only be understood if the stars are currently undergoing shell flashes (Wood and Zarro 1981). Both variables have had their mass loss rates determined by measurements of the circumstellar CO microwave emission (Wannier and Sahai 1986). A plot of the mass loss rates of Mira variables against pulsation period shows a clear increase of mass loss rate with period (Wood 1986; Schild 1989; Wood 1990). R Aql has a mass loss rate significantly in excess of the value given by the trend line while R Hya has a mass loss rate less that expected for a typical Mira variable of its period (Wood 1990). In both cases, the total amount of mass that will be lost at current mass loss rates over the ~500 year duration of the luminosity spike (~$5\times10^{-4}\ M_\odot$ for R Aql and ~$5\times10^{-5}\ M_\odot$ for R Hya) is small compared to a typical planetary nebula mass. These results do not seem to support the suggestion that shell flash induced luminosity spikes lead to planetary nebula ejection. Basically, if we accept that dust-enshrouded AGB stars such as OH/IR stars are currently in the stage of ejecting planetary nebulae, and if we adopt typical mass loss rates for these objects in the solar vicinity of ~$10^{-5}\ M_\odot\ yr^{-1}$ (Knapp 1987), then in 500 years (the duration of the luminosity spike) only ~0.005 $M_\odot$ will be ejected, this mass being much smaller that a typical planetary nebula mass. Clearly, mass loss must occur over a significantly longer time interval, and planetary nebula mass loss must therefore occur mainly during the inter-flash, hydrogen burning evolution.

4. Low mass AGB evolution with empirical mass loss rates

In order to explore the process of planetary nebula ejection theoretically, Vassiliadis and Wood (1992a) have evolved stars in the mass range $0.89 \leq M/M_\odot \leq 5$ from the main sequence to the white dwarf stage. The most important feature of these calculations is the mass loss formula, which is an empirical one based on measurements of the mass loss rates

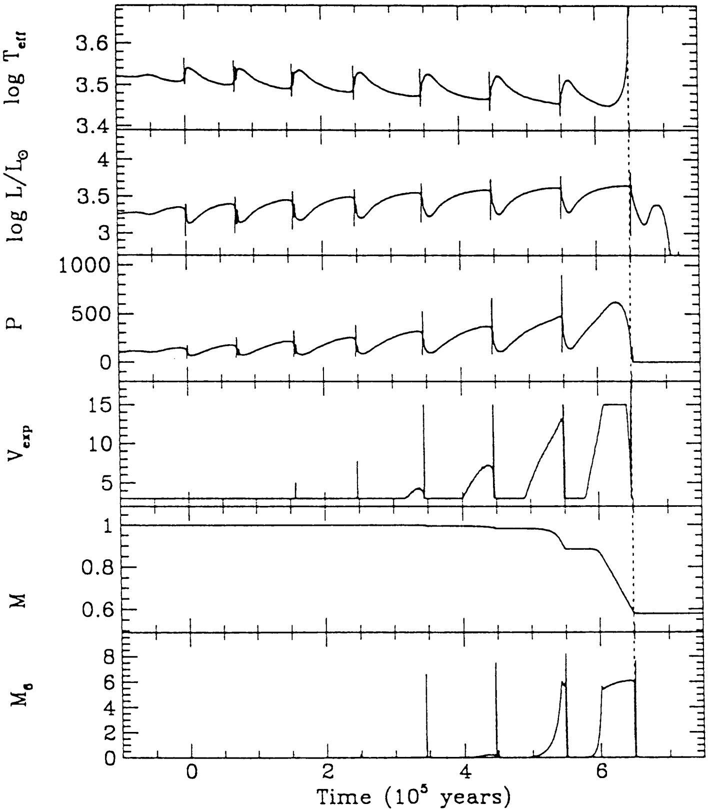

Figure 2. The time dependence of effective temperature T_{eff}, luminosity L, pulsation period P (days), stellar wind expansion velocity (V_{exp}), mass M ($M_\odot$) and mass loss rate $M_6(10^{-6}\ M_\odot\ yr^{-1})$ in a thermally pulsing AGB star of initial mass 1.0 $M_\odot$ and abundance (Y,Z) = (0.25,0.008). The vertical dotted line represents the end of the AGB phase and a change to a lower mass loss rate.

of Mira variables, OH/IR stars and other dust-enshrouded red giant stars. It is now believed that stellar pulsation is a crucial factor in the production of mass loss from AGB stars (Castor 1981; Hearn 1990) and plots of mass loss rate against pulsation period in these stars shows a clear exponential increase in $\dot{M}$ with P up to a limiting value which corresponds to the radiation pressure driven limit $\dot{M} = L/cv_\infty$ (Wood 1986; Schild 1989; Wood 1990). The mass loss formulae given in Wood (1990) were used in the calculations to be described here.

Some properties of a 1 $M_\odot$ AGB star evolving with mass loss are shown plotted against time in Figure 2; the zero of time coincides with the first major thermal pulse. The luminosity shows the characteristic spikes and the slow increase during hydrogen burning. The most important feature of these calculations is the behaviour of the mass loss rate. In all low mass ($M \lesssim 2.5\ M_\odot$) stars, the mass loss rate is negligible except during the last few shell flash cycles, and even then $\dot{M}$ is significant only during the high luminosity phases of hydrogen burning, and during the brief luminosity spike. However, the plot of total mass M against time shows that only a negligible amount of mass is lost during the luminosity spike: nearly all mass loss occurs during quiescent hydrogen burning.

The reason for the mass loss behaviour shown in Figure 1 is the very rapid increase in mass loss rate with pulsation period, which varies roughly as $R^2/M \propto L/MT_{eff}^4$ (Wood 1990). During the latter part of the hydrogen burning phase of the shell flash cycle, L is high and T_{eff} is low so the period (and mass loss rate) is correspondingly large. Once the stellar mass starts to decrease, the reduced total stellar mass acts to further increase P and $\dot{M}$. In the present calculations, the mass loss rate was not allowed to increase beyond the radiation pressure limit, which seems to coincide to within a factor of ~2 with the mass loss rates in very high mass loss rate AGB stars in the Galaxy (Knapp 1986), in the LMC (Wood *et al* 1992) and at the Galactic Centre (Whitelock *et al* 1991). This high mass loss phase can be equated to the *superwind* of Renzini (1981).

The fact that the superwind mass loss rate turns on and off indicates that there should be AGB stars with hollow circumstellar shells, or even multiple shells. If the central star has completely dissipated its envelope and has become hot enough to excite the surrounding circumstellar material, then the resulting object could appear as a multiple shell planetary nebula. The observational evidence for such situations is described in section 6. (It is worth noting at this point that if the maximum mass loss rate were set to *twice* L/cv_∞, consistent with errors in the measured mass loss rates and with the possibility of extra momentum being provided by scattering of photons within the circumstellar envelope, then complete envelope loss may occur in a single shell flash cycle for stars of $M \sim M_\odot$.)

As seen in Figure 2, the mass of an AGB star decreases significantly only during the last few shell flash cycles. This has important implications for stellar evolution calculations that seek to explain the dredge-up of carbon and s-process elements on the AGB. The dredge-up efficiency on the AGB is significantly enhanced if the envelope mass is large (Wood 1981). If most envelope mass is lost only during the last few flash cycles then, for the majority of AGB evolution, the full envelope mass is available to enhance the dredge-up process. However, if an enhanced Reimers (1975) mass loss formula is used on the AGB, mass loss occurs at lower luminosities than with the formula used above, and the likelihood of dredge-up occurring in model calculations will be reduced.

5. Intermediate mass AGB evolution

The behaviour of AGB stars of mass 5 $M_\odot$ (Figure 3) is quite different from the behaviour at low masses . In particular, the deep envelope convection in massive AGB stars rapidly extinguishes helium burning at the shell flash so that there is very little luminosity variation throughout the shell flash cycle. The mass loss increases steadily to superwind values over $\sim 10^5$ years and then stays at that value until the envelope is completely dissipated. Once the envelope mass is reduced below ~ 1.5 $M_\odot$, the deep envelope convection recedes and the surface luminosity variations seen in low mass AGB stars appear.

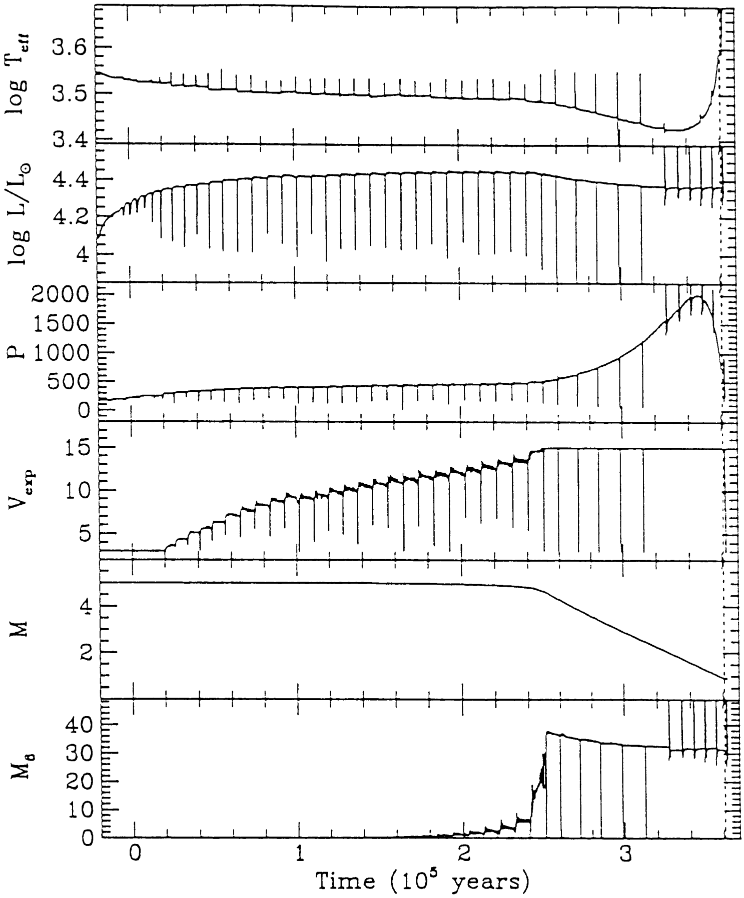

Figure 3. The time variability of a thermally pulsing AGB star of initial mass 5.0 $M_{\odot}$ and abundance (Y,Z) = (0.25,0.008). Symbols have the same meaning as in Figure 2.

6. Observational evidence for mass loss modulated by thermal pulses

Given the modulation of the mass loss rate by thermal pulses shown in Figure 2, we would expect at the very least that there should exist AGB stars in which a superwind mass loss episode had been turned off by a helium shell flash. Such stars would be surrounded by hollow circumstellar shells but would otherwise appear as normal M-, S- or C-type AGB stars.

Many stars with hollow circumstellar have now been identified using results from IRAS. Willems and de Jong (1988) found that detached dust shells were a common feature of carbon stars and they suggested that thermal pulses were the cause of these hollow shells. More recently, Zijlstra *et al* (1992) have used IRAS fluxes to find similar detached shells around oxygen-rich AGB stars.

More direct evidence for hollow shells around AGB stars has been found by Olofsson *et al* (1990, 1992). In these studies, the circumstellar shell has been detected by its CO microwave emission: mapping across the shell with the telescope beam clearly indicates the existence of a hollow shell. With the telescope beam centred on the star S Sct, Olofsson *et al* (1992) also found a weak central feature in the CO emission line profile that they interpreted as due to a weak, low velocity wind presently blowing from the central star. However, time-dependent hydrodynamic models of the winds around thermally pulsing AGB stars (Wood and Vassiliadis 1991; Vassiliadis and Wood 1992b) show that matter falls back onto the star during the low luminosity, post-flash evolution. The central CO emission peak found in S Sct could therefore be due to infalling material rather than a weak expanding wind.

Given the clear evidence for thermal pulse modulation of the mass loss shells around AGB stars, we would expect planetary nebula shells to show similar evidence for thermal pulse modulation. Multiple shell planetary nebulae are a possible result of the on-off-on existence of superwind mass loss on the AGB. Some multiple shell PN that have times between successive ejections which are consistent with the inter-pulse timescale are noted in these proceedings by Frank, Balick and van der Veen (1992).

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