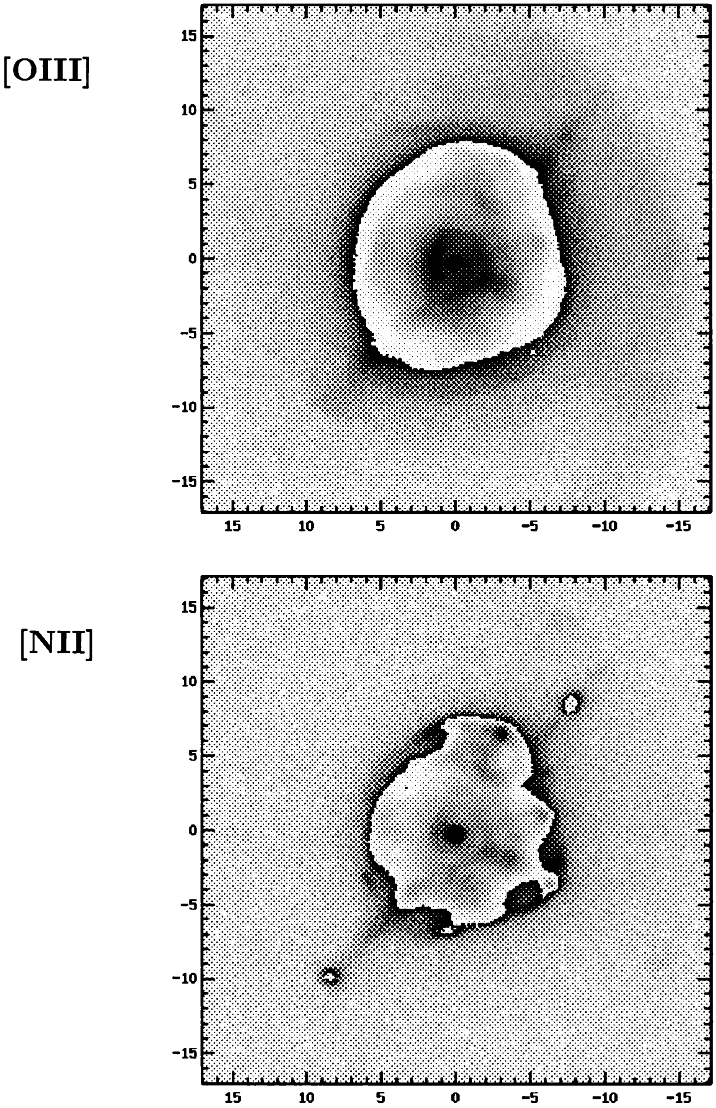
V. FROM AGB TO PLANETARY NEBULAE



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FINAL STAGES OF AGB EVOLUTION

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1. Introduction

The final stages of AGB evolution still remain difficult to study theoretically. From the stellar point of view, the main theoretical problems are the evolution of the stars (involving shell flashes and dredge-up of carbon and s-process elements), pulsation, and the production of mass loss by pulsation and radiation pressure on grains. In this paper I will discuss these topics. A recent review concentrating more on the circumstellar aspects of AGB evolution is given by Habing (1996).

2. Full AGB Evolution Calculations

There are very few complete AGB evolution calculations from the main sequence through to the planetary nebula phase with mass loss. In recent years, two such studies have been made, by Vassiliadis & Wood (1993) and Blöcker (1995). These two studies will be compared here.

A crucial ingredient in the AGB evolution calculations is the mass loss rate, at least as far as considerations of planetary nebula formation and evolution are concerned. The AGB stars with the most significant mass loss rates are those that were undergoing large-amplitude pulsation. Vassiliadis & Wood (VW) used an empirical relation between observed mass loss rate and pulsation period for their evolution calculations (see also Schild 1989). This relation shows an extremely rapid increase in $\dot{M}$ with P, at least up to P $\sim$ 600 days. Beyond that period, the observed mass loss rates are essentially constant at values of a few times 10^{-5} to 10^{-4} $M_{\odot}$ yr^{-1}. In view of this observed limit, VW limited $\dot{M}$ to the value L/cv which would be appropriate for a radiation pressure driven wind where photons emitted by the central star interacted once only with the outflowing wind. Recent calculations of radiation driven winds show that mass loss at rates up to 10

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times this limit are possible due to multiple scattering of photons (Netzer & Elitzur 1993; Habing *et al.* 1994).

A suggestion that the VW mass loss rates may be too low was made by Szczerba & Blommaert (1993) who showed that the limiting mass loss rates achieved by the 1-1.5 $M_\odot$ stars of VW are about a factor of 10 lower than the observed mass loss limit for stars with $P \gtrsim 600$ days. However, this may not be a real discrepancy since most of the observed AGB stars with very long periods are OH/IR stars near the Galactic plane or in the LMC with masses $\sim 5M_\odot$ (Baud *et al.* 1981; Wood *et al.* 1992).

VW found that most mass loss occurred during the higher luminosity segment of the hydrogen-burning phase of the helium shell flash cycle: the luminosity maximum at each shell flash is too brief for significant mass loss to occur then (at least with the mass loss rate limited as described above). Complete envelope ejection occurred over a small number of shell flashes. If the mass loss rate limit were increased, then fewer flashes would be required to dissipate the envelope and most stars with $M \lesssim 2M_\odot$ would probably require only one or two flash cycles to remove their envelopes.

In spite of the fact that the final VW mass loss rates are probably too low, the mass loss rates that are achieved are so large that most of the important results of these evolutionary calculations remain valid. In particular, the initial-final mass relation and the final AGB tip luminosities will be almost unaffected by removing the mass loss rate limit. VW showed that the AGB tip luminosities which their models predicted agreed very well with the observed AGB tip luminosities of clusters in the SMC and LMC, at least for initial masses $\lesssim 3\ M_\odot$. This is equivalent to saying the models reproduce the initial-final mass relation in the Magellanic Clouds, since the final mass is linearly related to the final AGB tip luminosity by the luminosity-core mass relation (Paczynski 1971).

Blöcker (1995) used a modification of the well-known Reimers dimensional mass loss law for his AGB evolutionary calculations, increasing the rate of increase in $\dot{M}$ up the AGB by multiplying the Reimers rate by $L^{2.7}$. Blöcker also added a $M_{ZAMS}^{-2.1}$ dependence, both factors being guided by the theoretical rates of mass loss produced during the pulsation calculations of Bowen (1988).

The Blöcker (1995) calculations reproduce the initial-final mass relation for Galactic objects (Weidemann 1987) reasonably well, although there are quite large uncertainties in this relation. However, the Blöcker (1995) mass loss formula overestimates mass loss rates for low mass stars with $M \lesssim 3M_\odot$. Many studies of planetary nebula nuclei (eg. Schönberner 1981; Gorny *et al.*, these proceedings) show that their masses M_{PNN} are very close to 0.6 $M_\odot$ (Schönberner 1981 finds $M_{PNN} = 0.58\pm0.03\ M_\odot$ while Gorny *et al.* find $M_{PNN} = 0.61\pm0.077\ M_\odot$). These masses presumably originate from stars with initial masses $\sim$1.2 $M_\odot$, typical of planetary nebula progenitors (O'Dell 1963). However, the Blöcker (1995) calculations require an initial mass of $\gtrsim$2.5 $M_\odot$ to produce a final mass of 0.6 $M_\odot$, and a 1.2 $M_\odot$ star produces a planetary nebula nucleus of mass $\sim 0.53 M_\odot$. Accurately defining AGB mass loss is still one of the most important problems confronting studies of AGB evolution.

3. Synthetic AGB Calculations

As well as uncertainty in the mass loss rate, there are major problems with our current theoretical understanding of dredge-up and nucleosynthesis in AGB stars. These problems arise largely because of uncertainties in the treatment of convection. Two parameters that are important for studying enrichment of AGB star envelopes by nucleosynthesis, and which theoretical evolution calculations should yield, are the minimum core mass M_c^{min} for third dredge-up on the AGB and the parameter λ which is the ratio of mass dredged-up per flash cycle to mass through which the H shell burns in one shell flash cycle. In order to try and tie these parameters down, a number of studies (Groenewegen & de Jong 1993,1994a,b; Marigo *et al.* 1996) of AGB evolution have been done adopting λ and M_c^{min} as adjustable parameters. These parameters, along with various others, depending on the study, were adjusted largely so as to reproduce the luminosity function of carbon stars in the LMC. The general finding of the above studies is that $\lambda \sim 0.65$ to 0.75 and $M_c^{min} \sim 0.58 M_\odot$. This contrasts with the values $\lambda \sim 0.25$ and $M_c^{min} \gtrsim 0.65 M_\odot$ generally found in current full AGB evolution calculations, depending on the abundance and mass of the AGB star (Wood 1981; Boothroyd & Sackmann 1988; Lattanzio 1989; Wood 1996). These results suggest that convection and convective overshoot, and consequent dredge-up, are probably more extensive in the envelopes of real AGB stars than in extant calculations. On the other hand, the synthetic calculations have many free parameters and simplifications, and it is hard to know the significance of their findings. In particular, it is generally assumed that λ and M_c^{min} are constants independent of stellar parameters whereas simple theoretical calculations show that these parameters are strong functions of stellar mass and abundance (Wood 1981). A clear demonstration of the dependence of λ on envelope mass is given by VW who show λ decreasing from $\sim$1 to 0 as the envelope mass in a 5 $M_\odot$ star decreases through $\sim$1.3 $M_\odot$ due to mass loss. Recent investigations also show that the details of the numerical treatment of dredge-up are as important as the treatment of convection (Frost & Lattanzio 1996). More detailed investigations of dredge-up in AGB stars are clearly needed.

The synthetic AGB calculations predict abundance ratios (ex. C/O,-

He/H) towards the end of AGB evolution. These can be compared with observed ratios in planetary nebulae in the Galaxy and the Magellanic Clouds (Groenewegen & de Jong 1994a; Marigo *et al.* 1996; Dopita *et al.* 1997). In the $(C/O, He/H)$ plane, the models predict that the lowest mass stars ($M \lesssim M_\odot$) have essentially no He or C enrichment due to dredge-up episodes while stars of mass $\sim 2.5M_\odot$ have maximum enhancement of C and He. In stars with $M \gtrsim 2.5M_\odot$, hot-bottom burning and the generally large envelope mass reduce carbon and He enhancements. The comparison with current observational data (Groenewegen & de Jong 1994a; Marigo *et al.* 1996) is not very encouraging. For stars in the Magellanic Clouds (Dopita *et al.* 1997), there do not appear to be any planetary nebulae with unenhanced C/O and He as predicted for the older, lower mass stars. If this is not a selection effect, then it indicates that third dredge-up and C star formation is occurring in even the oldest stars in the SMC and LMC.

4. Rotation in AGB Stars and Bipolar Planetary Nebulae

A successful scenario for producing bipolar planetary nebulae is to blow a fast wind from a post-AGB star into a remnant AGB wind distributed in some flattened distribution (eg. Soker & Livio 1989; Frank *et al.* 1993). However, the reason that the remnant AGB wind material is flattened remains to be determined. Studies of the mass loss envelopes around AGB stars show that such envelopes are generally round (see Habing 1996).

A possible mechanism for forming axially symmetric winds in AGB stars is to have the AGB star rotating. Dorfi & Höfner (1996) have recently studied the formation of dust-driven winds in rotating AGB stars and found that the winds produced do indeed have a strong density contrast from pole to equator. For example, in a model with $L = 10^4 L_\odot$ and rotation period 10 years, the ratio of equatorial to polar wind density is $\sim 10/1$, and the wind velocity at the equator is ~ 2.6 times the polar velocity.

Although a rotation period of 10 years may seem slow, it is in fact enormous in the sense that if the star were taken back to the main-sequence conserving angular momentum, it would be rotating at ~65 times breakup speed. In order to have a rotation period of 10 years, it would need to have acquired additional angular momentum through an event such as a common envelope binary merger. Han *et al.* (1995) have examined the frequency of such mergers and conclude that $\sim 30 - 40\%$ of stars have companions close enough that they could suffer a binary merger on the AGB. This mechanism might therefore offer a way of producing an AGB wind with a pole-to-equator density contrast needed for the production of bipolar planetary nebulae.

There is one AGB star that has recently been found to be rotating at the rate expected after a binary merger. Barnbaum *et al.* (1995) find that the carbon star V Hya has $v \sin i \sim 12$ km s^{-1}, compared to the model of Dorfi and Höfner (1996) which has $v \sin i \sim 7$ km s^{-1}. Another very interesting outcome of the Barnbaum *et al.* study of V Hya is that the rotation velocity varied with the phase of the pulsation cycle in the way expected if envelope angular momentum were conserved during inward-outward envelope pulsation. On the negative side, Barnbaum *et al.* examined a total of 74 carbon stars in total and only V Hya showed any detectable rotation. This indicates that AGB mergers may not be as common as predicted by Han *et al.* (1995).

The stellar wind emanating from V Hya has recently been studied by Kahane *et al.* (1996). They find a bipolar wind with an equatorial velocity of $\sim$7.5 km s^{-1} and polar velocity of $\sim$50 km s^{-1}. This contrasts with the Dorfi and Höfner models which have higher velocity in the equatorial direction than in the polar direction (although a reinterpretation of the Kahane *et al.* observational data, assuming higher equatorial velocity, might be possible). In addition, the fastest velocities obtained by the dust-driven wind models are $\sim$20 km s^{-1} rather than $\sim$50 km s $^{-1}$. So the role of rotation in shaping the bipolar wind in V Hya is unclear at this stage.

5. Variability on the AGB

A long-standing problem regarding variability on the AGB is the identification of the mode of pulsation (Willson 1982; Wood 1990). There have been some new observations in the last few years that leave the problem as confusing as ever. On one hand, Haniff *et al.* (1995) have measured angular diameters for a number of Mira variables and shown that the derived linear diameters are not compatible with fundamental mode pulsation, at least for masses $\lesssim 2M_{\odot}$. On the other hand, Wood & Sebo (1996) have examined the $(K, logP)$ relation for LPVs in the LMC and find that, as well as the well-known sequence for Miras, there is another parallel sequence corresponding to LPVs with $logP$ smaller by ~ 0.35. The simplest interpretation of these sequences is that the Miras are fundamental mode pulsators while the second sequence corresponds to semi-regular variables pulsating in the first overtone mode. Theoretical estimates for the periods of the LMC Miras also suggest that the pulsation mode is the fundamental. A solution to the mode identification problem is in sight, with new infrared estimates of Mira angular diameters being made, and the determination of $(K, logP)$ relations for large samples of LPVs found in microlensing surveys underway.

Finally, an interesting recent result concerning variability on the AGB is the finding that oscillations with periods of $\sim$500 to 2000+ days can develop spontaneously in the dust-driven winds of carbon stars (Fleischer *et al.* 1995; Höfner *et al.* 1995). These oscillations are driven by a complex interaction between grain formation, radiative transfer and radiation pressure on the grains. Winters *et al.* (1994) show examples of observed light curves and computed light curves which they think might be explained by this exterior κ-mechanism.

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