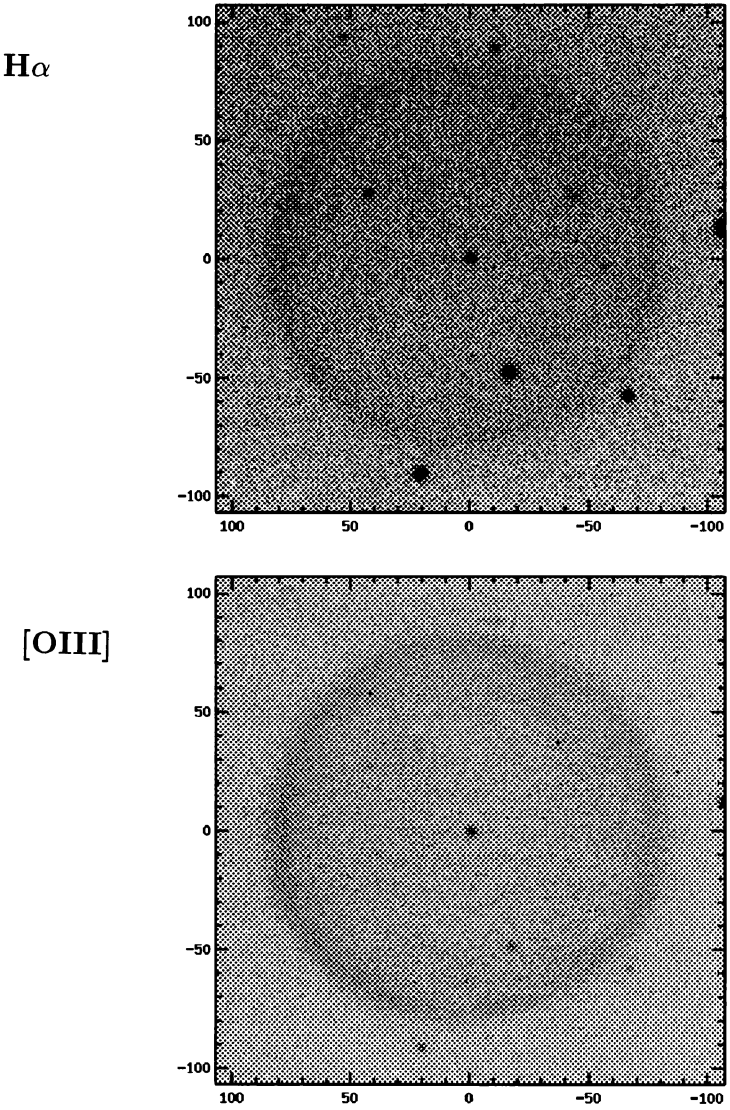
VIII. PLANETARY NEBULAE IN EXTRAGALACTIC SYSTEMS



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HUBBLE SPACE TELESCOPE OBSERVATIONS OF PLANETARY NEBULAE IN THE MAGELLANIC CLOUDS

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Abstract. We present the results of our major HST study of the evolution of PN in the Magellanic Clouds. This consists of imaging studies in [O III] and FOS UV spectroscopy. These data are then used in theoretical photoionisation models in conjuction with ground-based spectrophotometry, absolute flux and expansion velocity and density to derive self consistent diameters, ages, masses, and nebular abundances and to accurately place the central stars on the H-R Diagram. We find that observed sizes and ages can be reconciled with evolutionary theory provided that the He-burners outnumber the H-burners in the approximate ratio 2:1. For the LMC observed abundance patterns are qualitatively consistent with the (mass-dependent) operation of the various chemical dredge-up processes as predicted by theory. However, the observed dredge-up efficiencies do not agree with current theory. Finally, since core masses are determined with adequate precision, we are able to derive, for the first time, the metallicity age relation for of the LMC. We find that the base metallicity of the LMC rapidly increased ~ 2 Gyr ago, consistent with the age of the burst of star formation inferred from field stars and clusters.

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1. Introduction

The final evolution of stars from the tip of the Asymptotic Giant Branch (AGB) through the planetary nebula (PN) stage and towards the White Dwarf configuration represents a fascinating stage of stellar evolution. During the Asymptotic Giant Branch (AGB) phase, a complex series of thermal-pulsing events has occurred, producing chemical processing and dredge-up into the envelope, and accompanied by rapid and episodic mass-loss. This is terminated by a final envelope ejection event which may, or may not, be correlated with the phase of the He-flash cycle. All these processes affect the subsequent evolution in the PN phase, and are still relatively poorly understood. Nonetheless, rapid theoretical progress into these questions has been made in recent years (Schönberner 1983, Weidemann, 1987; Alongi *et al.* 1993; Vassiliadis and Wood 1993; Bressan *et al.* 1993; Chiosi and Marigo, 1996). This theory needs to be tested against observation.

For Galactic objects, such tests are beset by uncertainties in the PN distance scale which can be resolved by studying a population at known distance with low field reddening. The Magellanic Cloud PN are ideal for this. At optical wavelengths this population has already been studied in detail both by us and the University College group. Data on the line fluxes, the nebular densities, the expansion velocities and the kinematics have all been obtained (see the review by Barlow, 1989, also Dopita *et al.* 1985a,b; Meatheringham *et al.* 1988a,b; Wood, Bessell, and Dopita, 1986; Wood *et al.* 1987; and Jacoby, Walker and Ciardullo 1990; Meatheringham and Dopita 1991a,b). Furthermore, the IUE satellite has provided valuable data on dredge-up species such as C (Aller,1987; Reyes *et al.*, this conference; Leisy and Dennefeld,in press).

However, the key observational parameter not easily accessible to ground-based observation is the size and internal morphology of the nebula. From direct imaging, sizes can be derived for only the largest PN (Jacoby 1980; Wood *et al.* 1987; Jacoby*et al.* 1990; Jacoby and Kaler 1993). Speckle interferometric techniques help (Wood, Bessell, and Dopita, 1986) but the data can be difficult to interpret, and is often ambiguous. However, the imaging capability of the Hubble Space Telescope (HST) is well suited not only to measure the size but also to resolve details of the internal structure of the Magellanic Cloud PN (Blades *et al.* 1992). Furthermore, the poweful spectroscopic capability of the HST is ideal for the study of the UV spectra of these PN. In a series of papers, we have given the results of our integrated imaging and spectroscopy program (Dopita *et al.* 1993, 1994, 1996, 1997; Vassiliadis *et al.* 1996, 1997) which forms the subject of this progress report. In all that follows, the distance of the LMC has been assumed to be 50 kpc.

2. Self-Consistent Photoionisation Modelling

For each PN observed, the UV spectrophotometry (Vassiliadis *et al.* 1996) was combined with ground-based data (Meatheringham and Dopita 1991a,b) to generate a self consistent set of de-reddened line intensities extending from 1216 Å to beyond 7300 Å in the red. Extremely valuable constraints are given by the HST imaging data (Papers III and VI). These consist of images in the [O III] λ5007 line, chosen because it is generally the brightest emission line in the optical. These providesizes, and structural information which can be used as input to the photoionisation modelling analysis.

These data are interpreted (Papers I, II and V) using the generalised modelling code MAPPINGS II (Binette, Dopita and Tuohy, 1985; Sutherland and Dopita 1992). The goal of this self-consistent nebular modelling is to match the modelled size, density, and structure of the nebula with observations, determine the degree of optical thinness of the nebula, find the luminosity of the central star which matches both the absolute luminosity of the nebula and the observed stellar continuum flux in the UV, derive the stellar temperature and the ionisation parameter which matches the ionisation and excitation, and finally, determine nebular chemical abundances which reproduce the global line spectrum.

Ideally, a fully self consistent photoionisation model should have a continuous, fully three dimensional density distribution. However, the observational constraints are still insufficient to define such a structure. In the actual modelling, a two zone model was generally adopted, consisting of an optically-thick isobaric component, and a (generally optically-thin) region with a density which strongly declines with radial distance from the central source. In the modelling, we match the extent and densities of these zones to reproduce the observed size, density and morphology of the nebula, and adjust the stellar parameters and abundances to provide an optimum global match to the observed spectrum.

We should not expect the abundances derived by this technique to agree with those given by the ionisation correction factor (ICF) technique that has been commonly applied in the past (Aller *et al.* 1987; Dufour 1991; Kingsburgh and Barlow 1994; Leisy and Dennefeld 1996). Firstly, the ICF technique relies on determining the electron temperature from temperature sensitive line ratios. Since these ratios are strongly affected by temperature fluctuations (Peimbert 1995, and references therein), the ICF method will always underestimate the abundances of the principal coolants. Second, since the ICF method is based on semi-empirical corrections for ionic abundances of unseen species which are ultimately based on optically-thick photoionisation models, it suffers from unquantifiable and large errors when faced with multi-zone real nebulae.

3. The H-R Diagram and Evolutionary Ages

If we simply compare the radius of the PN with its position on the H-R diagram, we find (as expected) that the smallest PN tend to lie on the earlier parts of the evolutionary tracks, while larger objects are generally located where older PN are expected to be found. However, at any point on the H-R diagram, a wide spread in sizes is found, which suggests that a single evolutionary model is inadequate to explain the observations. Likewise, if we use the size and expansion velocity to compute a simple dynamical age, we find a wide range of values at any point on the H-R diagram, which also points to heterogeneous evolution. Furthermore, the dynamical age computed in this way is always smaller, and generally much shorter than evolution theory would indicate.

From a theoretical viewpoint, it is clear that the evolution of the central star depends critically upon whether it is He- or H- burning. The H-burning PN are, on average more luminous than their He-burning counterparts. However, the time available for evolution of the PN shell is generally much shorter for the H-burners. These factors compete in determining the radius : age relation. Overall, the lack of any clear correlation of dynamical age and position on the H-R diagram might also result from the dynamical evolution of the PN nebular shells themselves. A general correlation between the excitation class and expansion velocity was found by Dopita *et al.* (1988). In general, excitation class tracks closely to the logarithm of the effective temperature (Dopita and Meatheringham, 1991a). Subsequently Dopita (1993) found that a better correlation existed relating expansion velocity to the position of the PNn on the H-R Diagram :

$$V_{exp}/\mathrm{km.s}^{-1} = -128\pm4 + 38\pm2\ [\ \log(\ T_{\rm eff}\ ) - 0.25\pm0.05 \log\ (L/L_{\odot})]$$

This empirical equation implies that the nebular shell undergoes acceleration during the period in which hydrogen can still be burnt, after which the shell coasts as the central star fades. This type of evolution is entirely consistent with the two-wind model (Kwok *et al.* 1978), in which the energy input of the fast stellar wind during early post-AGB evolution is sufficient to accelerate the material ejected from the central star during the final stages of the AGB.

Dopita *et al.* (1996, Paper IV) used this equation to provide a semi-empirical means of correcting the observed dynamical ages for the effect of accelertion of the nebular shell. In most cases the true age of the PN is a factor of two to three times longer than implied by the simple dynamical age. This is done in one of two ways. First, we use the position of the PNn on the H-R diagram from the photoionisation models in conjuction with the evolutionary tracks of Vassiliadis and Wood (1993) to estimate the initial main-sequence mass of the PNn on the assumption either that it has a H-burning or that it has a He-burning central star. With this mass, and using the observed radius, we can then read off the evolutionary age. The second way is to correct the dynamical expansion ages by a factor which accounts for the acceleration of the PN shell. The dynamical age is derived from the radius divided by the expansion velocity given by the gradient of the empirical radius : time relation at this radius. The correction factor is then the ratio of the true age to the apparent dynamical age. For the He-burners, there are two maxima on this relationship, the first corresponding to the initial acceleration phase of the PN, and the second correponding with the episode of hydrogen re-ignition, which enhances the stellar mass-loss rate and leads to a second episode of acceleration of the PN shell.

Finally, the timescales derived in this manner should be consistent with the time since the PNn left the AGB, as derived from evolutionary tracks. In some objects, the timescales agree provided the central star is assumed to be H-burning, and in others agreement is found only for He-burning tracks. This enables us to classify the PNn as either H-burning or He-burning. As a specific example consider the case of SMP20. The estimated nebular age as a He- burning object was 4750 years and as a H-burning object it was 4250 years. However, to get to the observed point on the H-R diagram as a He- burning star would take 6500 years, but an H-burning central star would only require 650 years. Clearly, then, only the He-burning scenario is consistent with all the observations for this object.

Dopita, Jacoby and Vassiliadis (1993) claimed, on the basis of the distribution of PNn on the H-R Diagram that the the majority of PNn in the LMC were He- burners. This viewpoint is not one that has been generally accepted in the past (*e.g.* Schönberner 1983, Blöker and Schönberner, 1991). However Wood and Vassiliadis (1993) argued that at least 40% of the PNn should be He-burning on the basis of the fraction expected to leave the AGB as a function of phase of the shell flash cycle, and taking into account the relative rates of evolution of the He- and H-burners accross the H-R Diagram. Our (small number) statistics suggest that ~45-70% are He-burners. This fraction could be easily accomodated within the theoretical expectations if the shell flash episode itself leads to a somewhat enhanced mass-loss, causing the PNn to preferentially leave the AGB as a He-burning star.

In Figure 1, we show the positions of the objects which we have so far classified as either H- or He- burning and which we have placed onto the H-R diagram. The images show how the He- burning objects are systematically much larger than their H- burning counterparts at any given point on the diagram, thanks to the slower rate of evolution of the He- burning central stars across the H-R diagram.

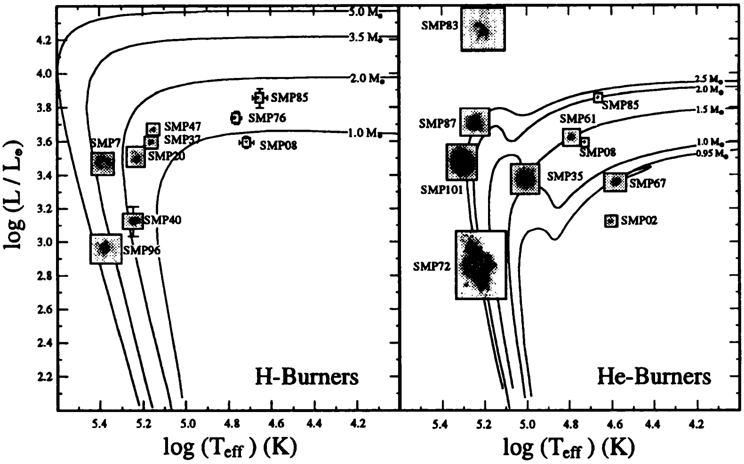

Figure 1. The H-R Diagram for the PN H-burning and He-burning objects. The HST image for each object is placed at the correct point on this diagram

4. The Metallicity : Age Relationship

Having accurately placed the PN central stars onto the theoretical $\log(L/L_\odot)$: $\log(T_{\rm eff})$ diagram, and having determined whether the stars are H- or He-burners, we can use the Vassiliadis and Wood (1993) evolutionary models to determine both the current core mass and the original mass of the star. The initial mass : core mass relationship is critical to the interpretation of these results. This is determined essentially by the mass-loss on the Giant and AGB phases, which channels a wide range of initial stellar masses into a narrow range of core mass. The mass-loss formulation adopted by Vassiliadis and Wood (1993) and used by Marigo, Bressan and Chiosi (1996) is to be preferred, since this ensures that the models match the period : luminosity relationship of the long-period variables, the maximum luminosity of the AGB stars, and the bolometric luminosity distribution of the carbon stars observed in the LMC. Combining the results of these two papers, we find that the relationship between initial mass, M, and final core mass, $M_{\rm core}$, can be expressed as:

$$(M_{\rm core}/M_\odot) = 0.5241 + 0.0438(M/M_\odot) + 0.00949(M/M_\odot)^2$$

This expression fits the models to better than 0.01Ms throughout the range. We also fit the Vassiliadis and Wood (1993) models to smooth functions of the H- burning and He- burning lifetimes, to give the age of the star in terms of its mass by:

$$(\tau/{\rm Gyr}) = 11(M/M_\odot)^{-3.1} + 0.46(M/M_\odot)^{-4.6}$$

We have used figure 1, and these equations to derive initial mass, core mass, and age of each PN. These can then be used in conjunction with the

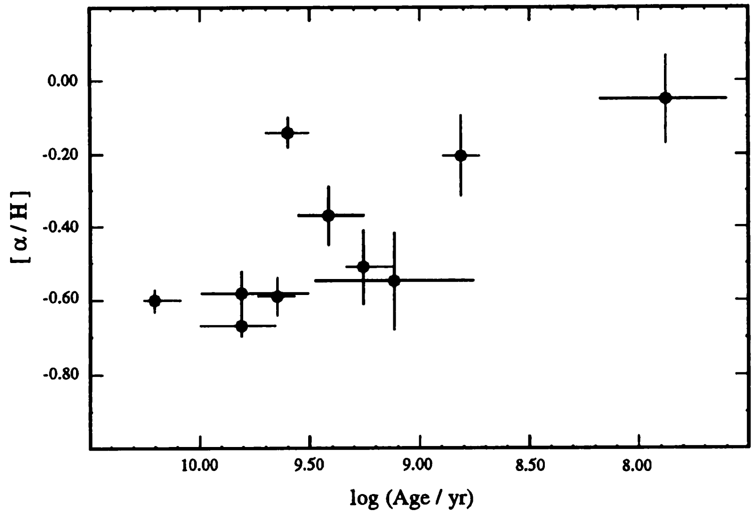

Figure 2. The metallicity history of the LMC as revealed by the HST observations. Note the rapid enrichment associated with a starburst that occured ~ 2 – 5 Gyr ago.

observed mean abundance relative to solar of the alpha process elements (O, Ne, Ar and S), $[\alpha/H]$, to derive the metallicity : age relationship for the LMC. This is shown in figure 2. We should note that Kaler and Jacoby (1990, 91) and Jacoby and Kaler (1993) had previously established a relationship between core mass and He and N abundance. However, it is difficult to separate changes in abundance of elements affected by dredge-up processes from the changes in abundance produced by the chemical evolution over time. Figure 2 reveals that for the LMC there was a long period of quiescence between ~ 15 Gyr and ~ 4 Gyr ago, during which the metallicity remained close to SMC values but that about 1-3 Gyr ago, there was a strong burst of star formation which more than doubled the metallicity.

This is in remarkable agreement with the data on both field stars and clusters. From colour magnitude diagrams of the field stars (Hardy *et al.* 1984, Frogel and Blanco 1983, Butcher 1977, and Stryker 1983, 1984), show that in the region of the Bar of the LMC, most of the star formation occurred in a major burst ~ 3 Gyr ago, and continued at a lower rate until ~ 0.1 Gyr ago. Cluster data (Girardi *et al.* 1995), shows a long period of quiescence, followed by an large rate of cluster formation 1-2 Gyr ago with a secondary peak at ~ 0.1 Gyr. An "age gap" characterised by very low star formation which lasted from 12 to 3 Gyr ago, and a rapid increase in metallicity in the age range 2-3 Gyr is also seen in the C-M diagrams of individual clusters (Da Costa, 1991). Finally, recent HST data on a field in the outer disk of the LMC Gallagher et. al (1996), shows a strong burst in star formation ~ 2.3 Gyr ago.

5. Mass Dependence of Dredge-up

The LMC data provides strong observational constraints upon the theory of mass and metallicity dependent dredge-up. According to theory, this is determined by three major dredge-up episodes and by "hot-bottom" burning (Iben and Renzini, 1983; Renzini and Voli 1981):

- The first dredge-up at the red giant stage, produced by the penetration of the convective envelope into regions which are partially CNO-burnt. The dredged-up material produces envelope enhancement of ^{13}C and ^{14}N, and a decrease in ^{12}C.

- The second dredge-up in the early AGB evolution of stars more massive than 3-5 $M_{\odot}$, when the hydrogen-burning shell extinguishes, and once again the base of the convective envelope dips into burnt material. Envelope enhancements of ^{4}He, ^{14}N and ^{13}C are produced.

- The third dredge-up during the thermally-pulsing AGB phase where, after each He-burning pulse, the convective envelope dips down, dredging up nuclear processed material rich in ^{4}He, ^{12}C and the s-process elements.

- Hot-bottom burning in more massive AGB stars ($M > 3M_{\odot}$). Convection cycles matter through the hydrogen-burning shell during the inter-pulse phase, with resultant partial CNO-cycling of the whole envelope. Significant ^{14}N, and possibly ^{4}He production, may occur.

In figure 3, we show the abundances of elements affected by these processes as a function of the abundance of the α-process elements relative to solar. The x-axis is a measure of both initial metallicity and of mass of the central star. There is a striking and systematic trend in the abundances of He, C and N with α-process abundance and/or mass. The enhancement of C at the low mass and abundance end indicates that the third dredge-up of C is important for such stars in the LMC, as is well known from studies of carbon stars. An important result is that the sum of the C + N abundances shows little systematic trend, in agreement with the results of Kaler and Jacoby (1990, 1991). This indicates that the third dredge up is significant at all masses. In stars of higher mass and/or abundance, hot-bottom burning appears to be operating efficiently to produce the very high N abundances observed, with most dredged-up C being converted to N. We agree with Leisy and Dennefeld (1996) that the C + N abundance appears

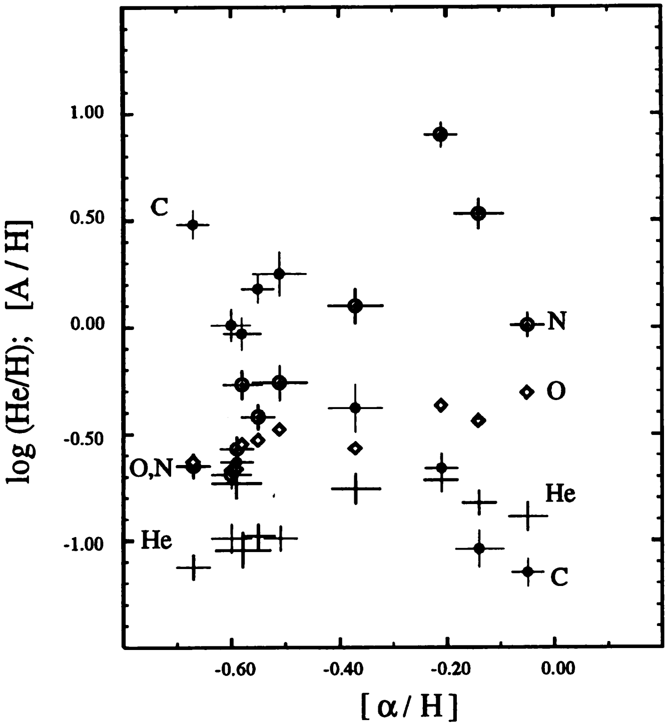

Figure 3. The abundances of the elements affected by dredge-up as a function of [α/H] for the LMC PN as derived from nebular modelling.

to be larger than the corresponding H II region value (*e.g.* Russell and Dopita, 1992), in contradiction to the results of Dufour (1991). However this effect can be understood as the result of third dredge-up combined with hot bottom burning, rather than the result of the first dredge up.

6. Conclusions

We have used our HST imaging and spectroscopic observations to derive self consistent diameters, ages, masses, and nebular abundances, and to accurately place the central stars on the H-R Diagram. Simple kinematic ages of the nebulae are systematically underestimated because of the acceleration of the nebular shell during its lifetime. Once this effect is corrected using a semi-empirical technique, we find a systematic trend in size accross the H-R Diagram. In addition, we can also separate the (younger) H- burning objects from the (older) He- burning objects at any point on the H-R Diagram. Apparently, He-burners outnumber H-burners in the approximate ratio 2:1.

The observed abundance patterns are qualitatively consistent with the (mass-dependent) operation of the various chemical dredge-up processes as predicted by theory. Dredge up of C during the thermal pulsing stage appears to be most important, and "hot bottom burning" transforms much of this C to N in the more massive stars. The spread in the α-process element abundances can be understood as being due to differences in core mass of the PNn, equivalent to differences in initial mass (or age) of the precursor star. We find that the base metallicity of the LMC rapidly increased ~ 2 Gyr ago, consistent with burst of star formation inferred from field stars and clusters.

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