New Views of the Magellanic Clouds
IAU Symposium, Vol. 190, 1999
Y.-H. Chu, N.B. Suntzeff, J.E. Hesser, and D.A. Bohlender, eds.

Planetary Nebulae in the Magellanic Clouds

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Abstract. The proximity, accurately known distance and low line-of-sight reddening give the ideal circumstances to pursue studies of individual stellar populations in the Magellanic Clouds. Here we show how our understanding of the evolution and chemical composition of the planetary nebulae in the Magellanic Clouds has been impacted by imaging and UV spectroscopic studies using the Hubble Space Telescope. Images provide sizes, internal morphological structure, absolute fluxes, and dynamical ages, while spectra allow us to place the central stars accurately on the H-R Diagram, and we can also examine the details of the evolution, of mass- and age- dependent chemical dredge-up processes, and infer the star-formation history of the Magellanic Clouds.

1. Introduction

The final evolution of stars from the tip of the Asymptotic Giant Branch (AGB) through the planetary nebula (PNe) stage represents a fascinating stage of stellar evolution. For Galactic objects, quantitative studies are beset by uncertainties in the PN distance scale. However, this problem is eliminated in the Magellanic Clouds, which provide a population of PN at known distance and having low field reddening. From the ground, this population has been studied in detail. Data on spectra, line fluxes, densities, expansion velocities and kinematics have all been accumulated in the last few years (see the review by Barlow 1989, also Dopita et al. 1985a,b; Meatheringham et al. 1988a,b; Meatheringham & Dopita 1991a,b). In addition, accurate positions have been obtained (Leisy et al. 1997), and the IUE satellite has provided valuable data on important dredge-up species such as C (Aller 1987; Leisy & Dennefeld 1996).

A key observational parameter is the size and internal morphology of the nebula. However, the nebulae are typically too small in angular extent and from the ground only fragmentary data has been obtained (Jacoby 1980; Wood et al. 1987; Jacoby et al. 1990; Jacoby & Kaler 1993; Wood, et al. 1986). 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 PNe (Blades et al. 1992; Stanghellini et al. 1999). Furthermore, the poweful spectroscopic capability of the HST is ideal for the study of the UV spectra of these PNe. Here we briefly describe the main results of our integrated imaging and spectroscopy program (Dopita et al.; Vassiliadis et al.; Papers I - VI; *see references*).

2. Evolutionary Theory

PNe are derived from low- and intermediate- mass stars. The exact initial mass limit (above which the star will explode as a supernova) is still somewhat uncertain, but is most likely 6 - 8 $M_\odot$. However, PNe more typically represent an intermediate-age stellar population, derived from stars having initial masses in the range 1 - 3 $M_\odot$. Stars evolve to the PNe stage at the end of their nuclear-burning lifetime, when the unburnt envelope mass becomes so low that it reveals the hot core of the star that remains. The theory of this phase hs made rapid progress recently (Schönberner 1983, Weidemann 1987; Alongi et al. 1993; Vassiliadis & Wood 1993; Bressan et al. 1993). Because of their low mass, the lifetime of the precursor star can be a considerable fraction of the age of a galaxy. From the Vassiliadis & Wood (1993) models:

$$\tau \sim 11.0\,(m/M_\odot)^{-3.1} + 0.46\,(m/M_\odot)^{-4.6}\,\mathrm{Gyr} \qquad (1)$$

The shell of gas, ionised in the PNe phase, was thrown off from the central star during the asymptotic giant branch (AGB) phase of evolution, assisted by the large radiation pressure. It is also enhanced by the shell flashes which result from burning helium under electron-degenerate conditions. As a result, the mass-loss rate is a very steep function of mass. This serves to channel a wide range of initial stellar masses (1 - $8M_\odot$) into a rather narrow range of final (White Dwarf) stellar mass (0.55 - $1.4M_\odot$). The relationship between initial mass, m, and final core mass, m_{core}, can be expressed as (Vassiliadis & Wood 1993; Marigo, Bressan, & Chiosi 1996):

$$m_{core}/M_\odot = 0.524 + 0.0438\,(m/M_\odot) + 0.0095\,(m/M_\odot)^2 \qquad (2)$$

Since the central star does not proceed beyond helium burning, and since much of the unburnt envelope is lost, the PNe provides a time-capsule of ionised material which has been chemically unchanged since the star formed, at least as far as the heavy elements are concerned. In principle, PNe may be used to probe the history of chemical enrichment in galaxies, although so far this has done very extensively (but see Dopita et al. 1997). For the lighter elements, and the heaviest elements, the material ejected as a PNe shell is not entirely pristine. A variety of mass- and metallicity- dependent convective phases dredge up partially hydrogen-burnt material from the boundary of the core during both the giant and asymptotic giant phases of evolution (Iben & Renzini 1983; Renzini & Voli 1981). These are:

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

- The second dredge-up in the early AGB stars of $m > 3 - 5M_\odot$, occurring when the hydrogen-burning shell extinguishes. This time envelope enhancements of ^{4}He, ^{14}N and ^{13}C are produced.

- The third dredge-up in the thermally-pulsing AGB phase. After each He-burning shell flash, the convective envelope dips down, dredging up material rich in ^{4}He, ^{12}C and the $s-$process elements.

- Finally, the so-called *hot-bottom burning* occurs in the more massive AGB stars ($m > 3M_{\odot}$) when convection in the stellar envelope cycles matter through the hydrogen-burning shell during the inter-pulse phase. Significant ^{14}N, and possibly ^{4}He production, may result.

3. Photoionisation Modeling of Magellanic Cloud PNe

For each PN, the UV spectrophotometry obtained with HST (Vassiliadis et al. 1996, 1998) was combined with ground-based data (Meatheringham & Dopita 1991a,b) to generate a self consistent set of de-reddened line intensities extending from Ly-α to beyond 7300Å in the red. In some cases, the S/N ratio of the UV data is even sufficient to study mass-loss in the central star (Bianchi et al. 1997)! Extremely valuable constraints to the modeling are given by the HST imaging data (Papers III and VI) which consist of images in the [O III] λ 5007Å line, chosen because it is generally the brightest emission line in the optical. These images not only provide the size, but also give detailed structural information which can be used as input to detailed photoionisation modeling analysis.

These data are interpreted (Papers I, II and V) using the generalised modeling code MAPPINGS II (Sutherland & Dopita 1992). The goal of this self-consistent nebular modeling is to match the modeled nebular size, density, and structure with observations, measure the degree of optical thinness of the nebula, derive the luminosity of the central star matching both the absolute luminosity of the nebula and the observed stellar continuum flux in the UV, estimate the stellar temperature and the ionisation parameter which matches both the degree of ionisation and excitation, and finally to derive the nebular abundances which matches 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 modeling, a two zone model was generally adopted.

4. Hydrogen - or Helium - Burners?

If we simply compare the radius of the PNe with its position on the H-R diagram, we find (as expected) that the smallest PNe tend to lie on the earlier parts of the evolutionary tracks, while larger objects are generally located where older PNe 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 and of its nebular shell depends critically upon whether it is He- or H-burning. He- burning stars are those which leave the AGB near the peak of the shell flash, while H- burners turn off the AGB between thermal pulses. In terms of relative numbers of these stars, we would expect to see only about 10-20% of He-burners. However, the observability of the PNe is strongly affected by the evolution. The H-burning PNe are initially 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, and they fade rapidly; before they have input much energy to accelerate the nebular shell into expansion. Nebulae around H- burners therefore rapidly evolve from small and bright to small and faint. On the other hand, the evolution of He- burners across the H-R diagram is slow and lazy, as hydrogen is re-ignited before the final fading of the central star. These stars put a lot more energy into the nebular shell while it is fairly bright, and so greater numbers of PNe will be observed in the bright phase, and these will be phyically much larger.

It is thus possible (Paper IV) to separate the Magellanic Cloud PN into H-burner and He- burner classes. At least half, and possibly that the majority of the luminous PNn in the LMC are associated with stars which left the AGB as He- burners - a viewpoint that would not have been generally accepted in the past (e.g. Schönberner 1983; Blöker & Schönberner 1991).

5. The Age-Metallicity Relation

From the position of the central stars on the theoretical $log(L/L_{\odot}) : log(T_{eff})$ Hertzsprung-Russell (H-R) Diagram, we determine the current core mass, the original mass, and the age of the star. These can then be used in conjunction with the observed mean abundance relative to solar of the α-process elements (O, Ne, Ar and S), $[\alpha/\mathrm{H}]$, to derive the metallicity : age relationship for the LMC.

This reveals that in 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. There is no evidence in this sample of any "halo" abundance objects. About 1-3 Gyr ago, there appears to have been a strong burst of star formation which more than doubled the metallicity. In recent times, star formation and the rate of chemical evolution slowed again. This is in remarkable agreement with the data on both field stars and clusters presented in this conference. For example, the latest cluster data (Girardi et al. 1995), shows a long period of quiescence, followed by an large rate of cluster formation 1-2 Gyr ago. An "age gap" is also seen in the colour magnitude diagrams of individual clusters (Da Costa 1991). Recent HST C-M data on a field in the outer disk of the LMC also show an age gap, with a strong burst in star formation starting ~ 2.3 Gyr ago (Gallagher et al. 1996).

6. Heavy Element Dredge-up

For the LMC our detailed abundance analyses (Dopita 1997; Paper V), shows a striking and systematic trend in the abundances of He, C and N with α-process abundance and / or stellar mass or age. A strong enhancement in C is found for old stars low mass. This indicates that the third dredge-up of C is important for such stars, 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 & Jacoby (1990, 1991). This indicates that the third dredge up is significant at all masses.

In younger stars of higher mass and abundance, "hot-bottom" burning appears to be operating efficiently to produce the very high N abundances, large N/C ratios and high He abundances observed, with most of the dredged-up C having being converted to N. These show the typical bipolar or butterfly morphology of the Peimbert's Type I; always suspected of being derived from relatively massive precursor stars. There is no sign of the expected dredge up of ^{22}Ne .

7. Conclusions

Imaging and spectroscopic studies of the PN in the Magellanic Clouds has permitted us to resolve details of the internal nebular structure, to obtain high signal to noise UV spectra of both the nebula and the central star; sufficient to examine the P-Cygni profiles of the mass-losing central stars in some cases. In conjuction with ground-based spectrophotometry, absolute flux, expansion velocity and density information, this data set permits fully self consistent diameters, ages, masses, and abundances to be derived for the nebulae, and the central stars can be accurately placed on the H-R Diagram. Thus, we have been able to examine the details of the evolution, and of the mass- and age- dependent dredge-up processes in a way which is just not possible for Galactic PN.

Acknowledgments. This paper summarises the efforts of all the observing team, Emanuel Vassiliadis, Peter Wood & Steve Meatheringham at Mt Stromlo, Ralph Bohlin at the Space Telecope Science Institute, Holland Ford at the Johns Hopkins University, Pat Harrington at the University of Maryland, and Ted Stecher and Steve Maran at Goddard Space Flight Centre. This paper is based upon observations with the NASA/ESA Hubble Space Telescope, obtained at the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS5-26555. The author wishes to acknowledge travel and publication support under a Major Grant from the International Science and Technology Division of the (Australian) Department of Industry, Science and Technology.

References

Aller, L.H., et al. 1987, ApJ, 320, 159

Alongi, M., et al. 1993, A&AS, 97, 851

Barlow, M. 1989 in Planetary Nebulae, ed. S. Torres-Peimbert, Kluwer : Dordrecht, p319

Bianchi, L., Vassiliadis, E., & Dopita, M.A. 1997, ApJ, 480, 290

Blades, J.C., et al. 1992, ApJ, 398, L41

Blöker, T., & Schönberner, D. 1990, A&A, 240, L11

Bressan, A., Fagotto, F., Bertelli, G., & Chiosi, C. 1993, A&AS, 100, 647

Da Costa, G.S. 1991, in The Magellanic Clouds , eds. R. Haynes & D. Milne, Kluwer: Dordrecht, p183

Dopita, M.A., et al. 1985a, ApJ, 296, 390

Dopita, M.A., Ford, H. C., & Webster, B.L. 1985b, ApJ, 297, 593

Dopita, M.A., et al. 1993, ApJ, 418, 804 (Paper I)

Dopita, M.A., Jacoby, G.H., & Vassiliadis, E. 1992, ApJ, 389, 27

Dopita, M.A., et al. 1988, ApJ, 327, 651

Dopita, M.A., et al. 1994, ApJ, 426, 150 (Paper II).

Dopita, M.A., et al. 1996, ApJ, 460, 320 (Paper IV)

Dopita, M.A., et al. 1997, ApJ, 474, 188 (Paper V).

Gallagher, J.S., et al. 1996, ApJ, 466, 732

Girardi, L., Chiosi, C., Bertelli, G., & Bressan, A. 1995, A&A, 298, 87

Iben, I. Jr., & Renzini, A. 1983, A&A, 21, 271

Jacoby, G.H. 1980, ApJS, 42, 1

Jacoby, G.H., Ciardullo, R., & Walker, A.R. 1990, ApJ, 365, 471

Jacoby, G.H., & Kaler, J.B. 1993, ApJ, 417, 209

Kaler, J.B., & Jacoby, G.H. 1990, ApJ, 362, 491

Kaler, J.B., & Jacoby, G.H. 1991, ApJ, 382, 134

Leisy, P., & Dennefeld, M. 1996, A&AS, 116, 95

Leisy, P., Dennefeld, M., Alard, C., & Guibert, J. 1997, A&AS, 121, 407

Marigo, P., Bressan, A., & Chiosi, C. 1996, A&A, 313, 545

Meatheringham, S.J., & Dopita, M.A. 1991a, ApJS, 75, 407

Meatheringham, S.J., & Dopita, M.A. 1991b, ApJS, 76, 1085

Meatheringham, S.J., et al. 1988a, ApJ, 327, 651

Meatheringham, S.J., Dopita, M.A., & Morgan, D.H. 1988b, ApJ, 329, 166

Renzini A., & Voli, M. 1981, A&A, 94, 175

Schönberner, D. 1983, ApJ, 272, 708

Stanghellini et al. 1999, ApJ, 510, 687

Sutherland, R.S., & Dopita, M.A. 1993, ApJS, 88, 253

Vassiliadis, E., et al. 1996, ApJS, 105, 375 (Paper III)

Vassiliadis, E., et al. 1997, ApJS, 114, 237 (Paper VI)

Vassiliadis, E., et al. 1998, ApJ, 503, 253 (Paper VII)

Vassiliadis, E., & Wood, P.R. 1993, ApJ, 413, 641

Wiedemann, V. 1987, A&A, 188, 74

Wood, P.R., Bessell, M.S., & Dopita, M.A. 1986, ApJ, 311, 632

Wood, P.R., et al. 1987, ApJ, 320, 178

Discussion

Norbert Langer: Do you find a systematic difference in the PN morphology when you compare the hydrogen burners with the helium burners?

Dopita: No, and indeed we would not expect to, since they are both drawn from the same stellar population.

Dominik Bomans: In the He-burner diagram one stood out with large size and location above the 2.5 $M_\odot$ tracks. Is it just chance to pick it or is there a special reason for this object?

Dopita: No, this is simply the faintest, oldest, and most evolved object in the sample.

Hans Zinnecker: You said PN theory is by and large in good shape, but there are problems in detail. What, then, are your recommendations for future theoretical work?

Dopita: Since we now have a reasonable age-metallicity relation for the LMC it would be very helpful to have stellar evolutionary tracks for these ages and initial metallicities. In addition, the observations can now be used to constrain the efficiencies of the various dredge-up episodes, which will tell us about the physics of the late phases of evolution. For example, there is no observational evidence for the dredge-up of ^{22}Ne predicted by current models such as those of Marigo.