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The Large Magellanic Cloud PN population

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Abstract. The Large Magellanic Cloud (LMC) and Small Magellanic Cloud (SMC) allow us to study late stellar evolution in environments that are respectively about a half and a quarter the metallicity of the Milky Way. With a known distance and low reddening, the LMC is an excellent environment to study PNe and conduct multiple studies. Over the past twelve months we have used the UKST Hα survey to complete our search for faint PNe in the outer most LMC beyond the 64 deg^2 area previously covered. Follow-up spectroscopy using AAOmega on the AAT and the 2.3-m telescope at Siding Spring Observatory have yielded a further 22 new LMC PNe while confirming the 8 previously known in the outer LMC. Medium- and high-resolution spectra have been used to measure fluxes and derive densities, mass and central star temperatures. A strong correlation is found between PNe and stellar density. This is visually displayed and given an empirical value of α = 1 PN / 2.5 $\times$ 10^6 L$_\odot$. The current [O III]-based PNLF, apart from providing an excellent standard candle, contains information about the parent population. The new PNLF, which extends down nine magnitudes, permits investigation of the faint end, the overall effects of internal extinction and provides clues to explain the insensitivity of the PNLF cutoff. When compared to the ionised density and mass of LMC PNe, the PNLF reveals it's bimodal characteristics. Two separate evolutionary paths are evident for young, evolving PNe.

Keywords. Planetary nebulae: General, Magellanic Clouds, surveys, kinematics.

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1. Introduction

We now have a unique and near complete dataset of LMC PNe thanks to progressive deep surveys over the past ∼40 years (see Reid & Parker 2006a for a summary). Individual PNe are close enough to gain spectroscopic confirmation (Reid & Parker 2006a,b, 2013) and morphological information (Stanghellini *et al.* 2000; Shaw *et al.* 1999). The PNe are additionally drawn from a sample that spans across an entire galaxy that has relatively low reddening (Kaler & Jacoby, 1990) and a well determined distance (Mould *et al.* 2000). In recent years considerable progress has also been made in understanding the evolutionary sequence of PNe. Multi-wavelength investigations of LMC PNe are revealing previously unknown correlations between morphology, age, carbon and oxygen content (Stanghellini *et al.* 2007; Reid 2014) while radio observations are allowing us to map the spectral index (Bojicic *et al.* 2007). A near-complete fraction of LMC PNe can now be plotted over an optical image of the galaxy to confirm the strong correlation between PNe and the local stellar density. This correlation is the basis of numerous new and expanding studies into the kinematic structure of galaxies in the Local Supercluster (eg, Coccato *et al.* 2009; Longobardi *et al.* 2015; Cortesi, *et al.* 2013).

In addition, we are gaining more insight into the structure of the planetary nebula luminosity function (PNLF). The PNLF has been used as an extragalactic distance indicator since the late 1970's (Ford & Jenner, 1978) and studied for it's physical properties since 1989 (Jacoby, 1989; Ciardullo *et al.* 1989). As a distance indicator it remains one

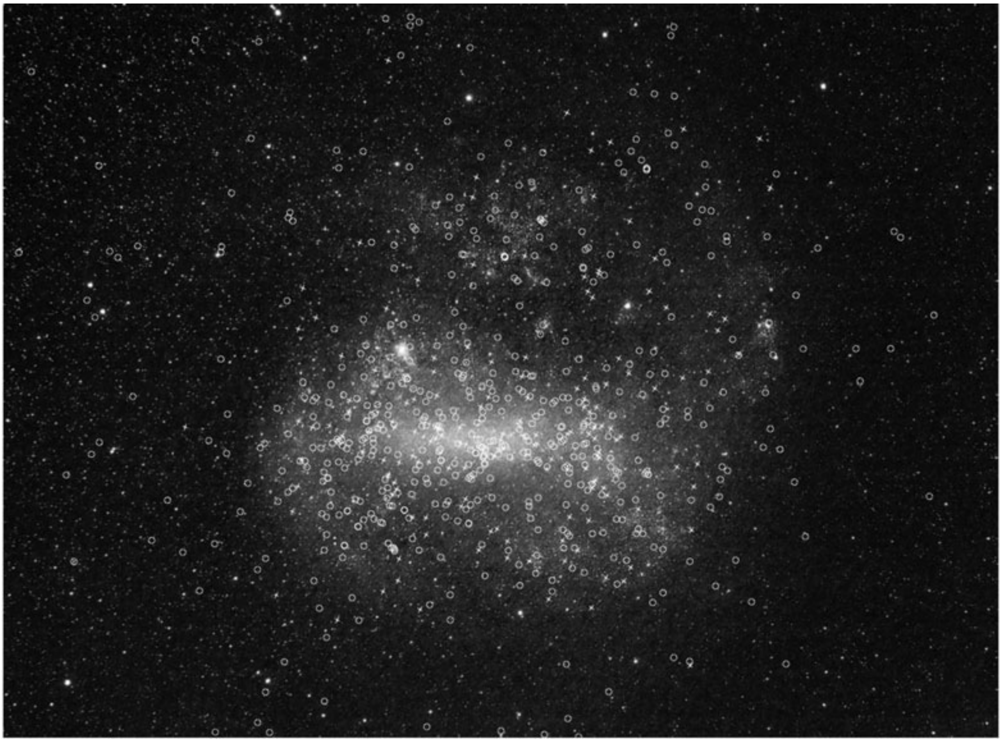

Figure 1. The positions of PNe currently known in the LMC. Circles represent the positions of non-type I PNe and crosses represent Type I PNe. LMC image credit: Primoz Cigler.

of the most important standard candles and the only one that may be applied to every large galaxy where PNe are detected, regardless of Hubble type. A more comprehensive understanding of the physics behind the PNLF is slowly beginning to emerge thanks to the large number of PNLF studies in galaxies of varying metallicity (Dopita, *et al.* 1992) and comparisons of the PNLF at different wavelengths (Reid & Parker, 2010a; Reid, 2014). Added to this, the PNLF is now examined in terms of extinction, abundances, nebula density and mass.

2. PNe and stellar density

Fig. 1 shows an optical image of the LMC with PNe indicated to confirm the strong correlation they have with stellar density. This image serves as visual confirmation that the PN population size, when scaled to the available completeness limits, directly correlates with the visual magnitude of a galaxy. The resulting correlation provides the number of PNe $L^{-1}_{\odot bol}$ or "α ratio" (Magrini *et al.* 2003). Please see Reid (2012) for further details. Visible number densities provide information about past kinematic evolution such as possible ram pressure stripping of PNe by a hot intercluster medium. In addition, the α parameter and the PNLF correlate with the age, colour and metallicity of the LMC's progenitor stellar population.

The stellar core mass evolution directly affects the PN lifetime since it depends on the central star temperature ($T_{eff} \simeq 10^5$ K) during the hot post AGB phase. With an increase in the hot post AGB lifetime with increasing dynamical ages and metallicities, the τ_{HPAGB} is somewhat equivalent to Fuel/l_{HPAGB}, where l_{HPAGB} is the luminosity

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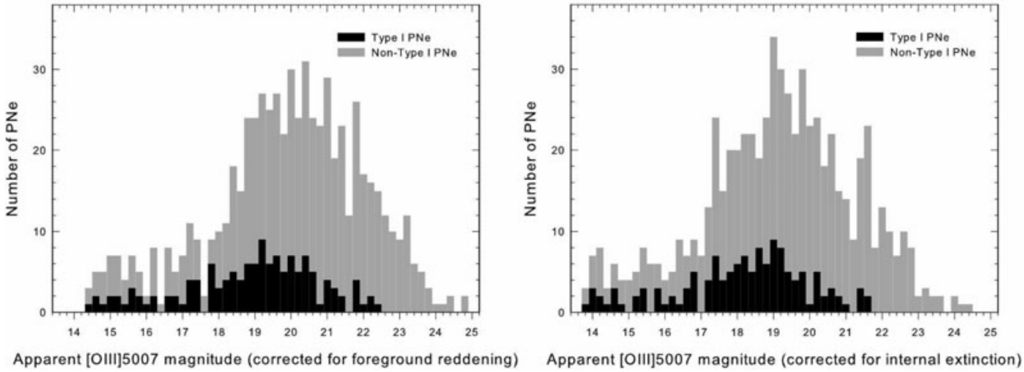

Figure 2. The LMC PNLF with all PNe corrected for foreground reddening (left) and additionally corrected for internal reddening (right). Type I PNe are indicated by the black colour bars.

of the central star at the onset of the PN stage. The luminosity-specific PN density may be described as:

$$\alpha = \frac{\mathrm{N}_{PN}}{\mathrm{L}_{SSP}} = ß\,\tau_{PN} = ß\min\{\tau_{HPAGB}, \tau_{dyn}\}. \tag{2.1}$$

Using this equation, Buzzoni *et al.* (2006), applying the theory of simple stellar populations (SSP) (Renzini & Buzzoni, 1986 and Buzzoni, 1989) to the local group found a value of

$$\alpha = 1 \text{ PN}/1.5 \times 10^6 \mathrm{L}_\odot. \tag{2.2}$$

This relation, however, is weakly dependent on the age, metallicity, morphological type of the galaxy (Buzzoni, Arnaboldi, 2006) and the degree of star formation at the time the PN progenitors were forming. To find the luminosity-specific number of PNe for the LMC, the luminosity is then directly calibrated to the near-complete PN number density currently found in the LMC. The PN numbers supplied by Reid & Parker (2013) and Reid (2014) suggest there may not be many more than 740 genuine PNe in the LMC. Using this data and allowing for a small 5% of faint undiscovered LMC PNe, the current estimate is

$$\alpha = 1 \text{ PN}/2.5 \times 10^6 \mathrm{L}_\odot \tag{2.3}$$

where the metallicity is ~ -1.15. The difference between equations 2.2 and 2.3, when corrected for small effects of metallicity and star-forming rates, intrinsically predicts that not every star in the 1 - 8 stellar mass range will go through the PN evolutionary stage.

3. The physics underlying the LMC PNLF

It is now known that the position of the bright end of the PNLF is slightly sensitive to metallicity but other aspects such as the mass, density and age of PNe at the bright end have previously been difficult to determine. The luminosity of the [O III] 5007 line is directly linked to the luminosity of its central star and thus, to its mass. This being the case, it is fair to assume that the bright end of the PNLF will quickly fade, however, the bright end is universally well populated while observations and simulations show that it does not appear to dramatically fade. These [O III]-bright PNe have large circumstellar envelopes and high dust content as a direct result of their high mass. The dust acts

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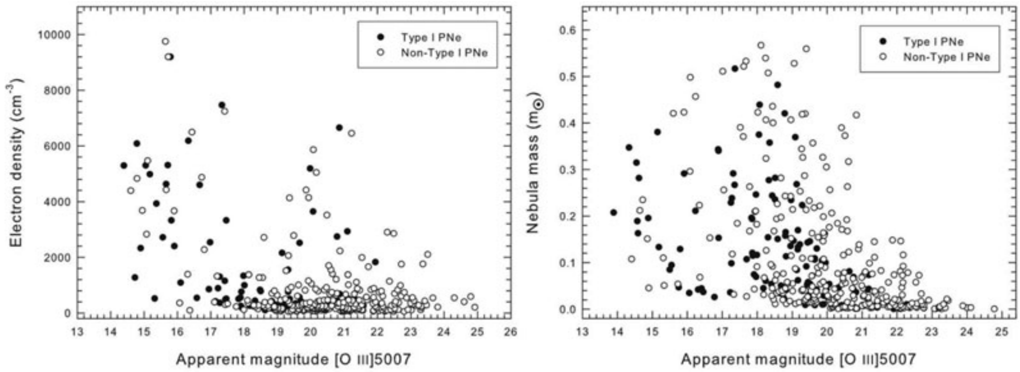

Figure 3. Electron density versus [O III] 5007 apparent magnitude (left) and nebula mass versus [O III] 5007 apparent magnitude (right). Type I PNe are indicated by the filled circles.

to dim the [O III] flux, thereby ensuring that it does not exceed the PNLF bright-end cutoff known as M*. Proof of this comes from the LMC, where the PNLF, corrected for foreground reddening, is almost a magnitude fainter than the intrinsic PNLF which is corrected for internal reddening (Fig. 2, see also Reid & Parker 2010a). Constant destruction of the dust such as polycyclic aromatic hydrocarbons by UV emission from the central star (Reid 2014) has the effect of gradually thinning the optical opacity. The [O III] brightness, while gradually declining, will therefore appear to remain more or less stable as the dust disperses.

In star-forming galaxies, there are a larger proportion of PNe with high-mass cores. This will directly affect the shape of the bright end. Depending on the metallicity of the galaxy, there will be a dip in the PNLF between $\sim$2 and $\sim$4 mag down from M*. This dip, suggesting a rapid decline in [O III] flux, is a natural consequence of the cooling high-mass core and confirms the bimodal PNLF expected to arise from the post-AGB stage (Vassiliadis & Wood, 1994).

Abundances were determined for all the LMC PNe using electron densities from the [S II] 6717/6731 lines and electron temperatures from [O III] (4959 + 5007/4363) for oxygen and from [N II] (6548 + 6583/5755) for nitrogen. An empirical method of abundance determination, similar to that of Aller (1984) was then used. This system applies ionisation correction factors based on grids of photoinisation models of nebulae as used by Kingsburgh & Barlow (1994). The measured intensity ratios of the lines emitted by the ions provide the abundance ratio. In Fig. 2 the PNe are separated into non-Type I and Type I PNe whose abundances satisfy the criteria where He / H > 0.10 and N$^+$/O$^+$ > 0.25. This division can be significant because it marks the position where the mass, based on LMC metallicicities, would allow Hot Bottom Burning to convert carbon to nitrogen. In terms of the positions of Type I PNe in the LMC, Fig. 1 shows that they are mainly found within the dense inner regions. With the exception of the tidally stripped star cloud comprising LMC A to the north, there are less than ten Type I PNe in the outer LMC.

Fig. 2 shows that there is no increase in the number or proportion of Type I PNe at the bright end. The ratios of Type I to non-Type I remain relatively consistent until about mag 21, seven mag down the PNLF, fainter than which, there are only 13 Type I PNe and none in the faintest $\sim$2 mag. It is also worth noting that while correction for internal extinction shifts the PNLF to the left by almost a mag, individual PNe may be shifting anywhere from 0.2 mag to 1.5 mag. The overall shape of the PNLF following internal correction is surprisingly similar, however, the non-type I PNe on average shift

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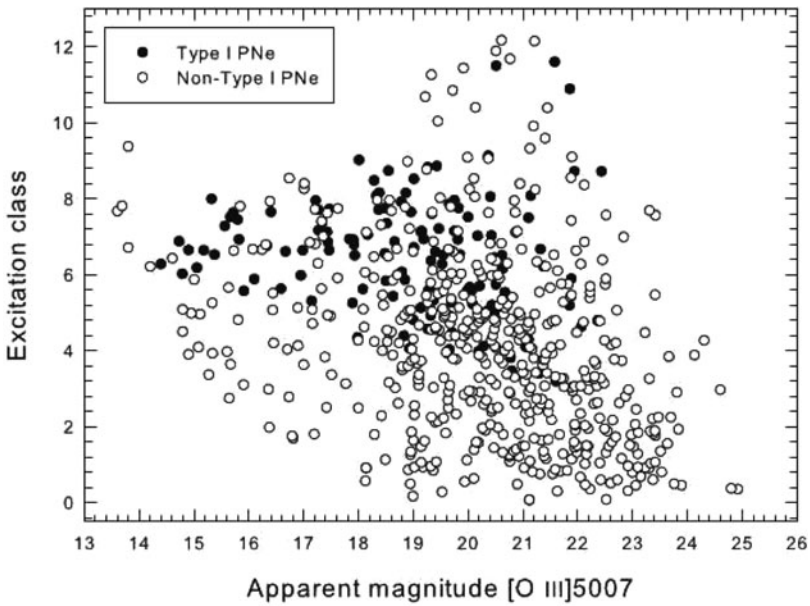

Figure 4. Excitation class versus [O III] 5007 apparent magnitude. Type I PNe are indicated by the filled circles.

0.3 mag more than the Type I PNe. A comparison shows that the dip at the bright end is more pronounced where only PNe on the main bar are used to create a PNLF. The dip in Fig. 2 is less prominent due to adding the ∼100 mainly non-Type I PNe from the outer LMC. This indicates the low likelihood of finding star-forming regions away from the main stellar bar.

Comparing the [O III] 5007 magnitude with the electron density within the nebula, a broad range of densities from $\sim 120\,\mathrm{cm}^3$ to $9800\,\mathrm{cm}^3$ are found at the bright end (the brightest three mag of the PNLF). Surprisingly, a similar progression of high to low density levels can also be seen above the bulk of PNe in the mid-luminosity range providing strong evidence for a bimodal progression of evolution through the post-AGB phase. While the majority of PNe evolve with densities below $\sim 1\,200\,\mathrm{cm}^3$, the data shown for LMC PNe in Fig. 3 (left) suggest that there may be two entry levels for stars commencing their PN evolution. PNe that enter at the bright end are less likely to remain there as their densities reach low levels. Young PNe entering the PNLF at lower [O III] luminosity levels may not experience the dramatic loss in luminosity experienced by their high mass cousins. Their densities nonetheless decrease while their lower mass slows the evolutionary process, sustaining their luminosities in this mid-region of the PNLF for a long period of time. Similarly, in Fig. 3 (right) the nebula mass, determined using the Hβ flux (see Meatheringham *et al.* 1988 for method) reveals a separate evolutionary path for highly luminous PNe. Both of these plots very strongly confirm the bimodal nature of the PNLF.

The excitation class of LMC PNe was determined using the formula of Reid & Parker (2010b). The excitation class provides a strong indication of the central star's excitation and may be used as a proxy for the central star temperature. When applied to the [O III] 5007 magnitude of LMC PNe, a general anti-correlation is evident so that no [O III]-bright PNe are found in the low excitation bracket (Fig. 4). The Type I PNe are only found in the higher 50% of PNe at each magnitude level. These PNe were

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massive AGB stars (M > 3.5-4.0 $M_\odot$) allowing them to undergo the third dredge-up via *hot-bottom burning* whereby hydrogen-burning took place in the hot deepest layers of the convective envelope during quiescent periods. PNe with excitation classes greater than nine are likely to be optically thin PNe.

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Discussion

Peimbert: Is the extinction greater at the foreground or internal level?

Reply: In the majority of cases the foreground extinction is more significant however the LMC is not homogeneous and some PNe are highly self reddened.

Balick: I'm blown away by the image of the PNe over the LMC. Could you show that again?

Reply: It proves the correlation between PNe and stellar population which is important for extragalactic kinematic studies (Fig. 1).

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