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<tbody>
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<tr>
<td><strong>Citation</strong></td>
<td>Monthly Notices of the Royal Astronomical Society, 2015, v. 452 n. 2, p. 1402-1411</td>
</tr>
<tr>
<td><strong>Issued Date</strong></td>
<td>2015</td>
</tr>
<tr>
<td><strong>URL</strong></td>
<td><a href="http://hdl.handle.net/10722/214493">http://hdl.handle.net/10722/214493</a></td>
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Four new planetary nebulae towards the Small Magellanic Cloud

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ABSTRACT
We present four new planetary nebulae (PNe) discovered in the Small Magellanic Cloud (SMC) from deep UK Schmidt telescope narrow-band H α and broad-band short-red ‘SR’ continuum images and confirmed spectroscopically. All new PNe show strong [N ii]/H α ratios in their spectra. We describe and detail the process of PN candidate selection based on wide-field multiwavelength imaging of the SMC and our subsequent spectroscopic confirmation and classification. We carefully reviewed archived information and available imagery for previous SMC PN detections and various other types of emission objects in the SMC as a training set to help identify new PN candidates. These four preliminary discoveries provide a 4 per cent increase to the previously known SMC PN population of ∼100. Once spectroscopic follow-up of all our newly identified SMC PN candidates is complete, we expect to increase the total number of known SMC PNe by up to 50 per cent. This will permit a significant improvement to determination of the SMC PN luminosity function and enable further insights into the chemical evolution and kinematics of the SMC PN population.

Key words: planetary nebulae: general – Magellanic Clouds.

1 INTRODUCTION

Planetary nebulae (PNe) represent an important but brief (~25 000 year), late stage of stellar evolution experienced by most low- and intermediate-mass stars (∼1–8 M⊙). They play a crucial role in understanding various aspects of late stellar evolution, such as mass-loss (Iben 1995) and the subsequent interstellar enrichment by the products of nucleosynthesis like oxygen, nitrogen and dust. Their ionized gas shells exhibit numerous, strong emission lines that are excellent laboratories for understanding plasma physics. PNe are visible to great distances due to these strong lines that permit determination of nebula size, age and expansion velocity. The luminosity, temperature and mass of their central stars (CSPN) can also be estimated (Preite-Martinez 1993; Gruenwald & Viegas 2000), as can the chemical composition of the ejected gas (Stanghellini, Shaw & Gilmore 2005). Determining PNe radial velocities also allows us to trace the kinematic properties of their host galaxies. Their complex morphologies provide clues to their formation, evolution and mass-loss processes. This shaping is thought to result from a variety of mechanisms, including radiation-driven stellar winds (Balick & Frank 2002), CSPN binarity (De Marco 2009; Miszalski et al. 2009a,b), magnetic fields (Blackman et al. 2001) and sub-stellar PN companions (De Marco & Soker 2011).

Knowing PNe distances is key since important physical quantities like total nebular mass, luminosity and evolutionary states of the CSPN, as well as the physical extent of inner shells and outer haloes are distance dependant (Ciardullo et al. 1999). However, study of Galactic PNe suffers from severe problems with distance determinations (van de Steene & Zijlstra 1994; Bensby & Lundström 2001; Smith 2015) though significant recent progress has been made (Frew, Parker & Bojicic 2015). Strongly varying dust obscuration across the Galactic plane and the presence of significant non-PN mimics have also biased studies based on previous Galactic PN catalogues, e.g. see Frew & Parker (2010). These distance and extinction problems are largely circumvented by studying PNe in nearby galaxies with well-determined distances and extinctions such as the Large and Small Magellanic Clouds (LMC and SMC, respectively). They are sufficiently close for detailed individual scrutiny by ground- and space-based telescopes such as the Hubble Space Telescope (HST; Stanghellini et al. 2003; Shaw et al. 2006). Studies between PNe residing in galaxies with different morphologies, metallicities, star-forming history and chemical evolution (Magrini 2006) can also be visually performed and would benefit from having statistically significant samples for comparison.

Population synthesis shows that a PN population, scaled to completeness limits, correlates with the visual magnitude of the host galaxy (Magrini et al. 2003). This allows the PN specific luminosity rate to be estimated for various Local Group galaxies (Jacoby 1980). Based on the theoretical luminosity-specific PN density, Buzzoni & Arnaboldi (2006) and Reid (2012) used best determinations of
bolometric luminosities and the current number of PNe known in Local Group galaxies to provide an estimate of the number of Local Group PNe that may yet be found.

The LMC currently hosts ∼740 confirmed PNe (Reid & Parker 2006a,b; Reid 2014) compared to the 800–900 expected from population synthesis, while the SMC only has ∼100 comprising only ∼46 per cent of the expected total of ∼216 (Jacoby & De Marco 2002) for a complete survey (8 mag down the PNLF). More recently, ∼2006a,b, 2013; Reid 2014) compared to the 800–900 expected from Group PNe that may yet be found.

Local Group galaxies to provide an estimate of the number of Local Group PNe based on the PNLF to be explored, provide a more complete SMC PNe sample. It is crucial to meaningfully study their evolution, the stellar evolutionary history of the SMC, the enrichment of the interstellar medium and the mass-loss history of their CSPN. These factors have helped motivate this current project.

2.1 SMC PN surveys

The earliest work on the SMC PN population was undertaken with a variety of modest aperture, wide-field, Schmidt-type telescopes fitted with objective prism dispersers (Henize 1956; Lindsay 1961). The first major study (Henize 1956) published the positions of 236 emission-line stars and 532 emission nebulae in both Magellanic Clouds. 20 of the nebulae in the SMC were listed as PNe while 9 were considered to be good PN candidates. Lindsay (1961) produced a catalogue of 593 ‘unresolved’ emission-line objects in the SMC, of which 26 are considered to be PNe and 13 are probable PNe.

Sanduleak, MacConnell & Philip (1978) later published another catalogue, based on a collection of various types of deep objective-prism photographic plates, listing 25 sources as PNe and only three as PN candidates. Jacoby (1980) reported 8 known PNe and 19 candidates, while the work of Sanduleak & Pesch (1981) added 6 more candidates. Low dispersion objective prism spectra are indicative at best and a significant number of objects from these catalogues have never undergone proper higher resolution spectroscopic confirmation. Sometimes, the presence of emission lines other than Hα was enough for a source to be previously classified as a PN (Lindsay 1961). In many cases the presence of a continuum together with the Hα line was sufficient for the object to be classified as an emission-line star rather than a PN. Furthermore, a number of objects have only been observed once at low resolution (Morgan 1995) without important diagnostic line ratios being resolved.

Most recently, Jacoby & De Marco (2002) using the ESO 2.2 m telescope with the 8k × 8k mosaic CCD camera, surveyed 2.8 deg2 of the central SMC region searching for faint PNe using on and off-band [O iii] imaging and follow-up confirmatory spectra of candidates with the CTIO 4 m telescope. They reported 59 confirmed PNe including 25 new discoveries which still represent the single, largest increase in SMC PNe till now. They note a high incidence of new, faint PNe exhibiting strong [N ii]/Hα ratios compared to that seen in the previously known ‘brighter’ SMC PNe population. They attribute this to a selection bias to favour chemically enriched type I PNe (Kingsburgh & Barlow 1994) from higher mass and
therefore younger progenitors being both shorter lived and partially self-obscured by dust and so harder to detect.

3 A NEW POPULATION OF SMC PNE

SMC PNe are an effectively colocated population in a coherent system at known distance. As H α emission alone cannot distinguish between many emission-object (EmO) types and considering [O III] emission is weak or even absent in some low-excitation PNe or those that are heavily obscured (Frew & Parker 2010), a different, systematic approach is required. This is both to confirm the veracity of many of the previously identified SMC PNe currently lacking unambiguous spectroscopic confirmation and to uncover new candidates. We have adopted a multibandwidth approach. First we used a deep, narrow-band, arcsecond resolution H α and matching broadband red continuum ‘SR’ digital image data for over 120 deg². We have carefully examined the UKST H α to our digital H α image map. If two sources had similar but slightly different coordinates they were considered to be the same object if only one clear emission source was evident in our own H α data at or near the reported location. Conversely, if a catalogued source had no apparent emission equivalent in our data or related imagery, e.g. from the Magellanic Cloud Emission-Line Survey (MCELS; Smith et al. 2005), then its identity as a true emission-line source is called into question. Detailed results from this evaluative study will be presented in a later paper. An astrometric WCS grid, accurate to ~0.2 arcsec, has been carefully applied to our digital H α and ‘SR’ SMC maps following standard SuperCOSMOS procedures, e.g. Hambly et al. (2001a,b). This coordinate system provides the basis for all new and previously identified PNe presented in this and our subsequent papers.

As a result of this careful cross-checking, a unique list of 252 objects, including PNe, emission-line stars, red giant branch stars, asymptotic giant branch stars, spectroscopic binaries and other miscellaneous EmOs were compiled. These objects were then divided in two groups. The first comprising 101 PNe (either previously confirmed or previously identified as a PN candidate) and the second 151 miscellaneous EmOs, such as young stellar objects, various types of emission-line stars, H ii regions, SNRs, etc. This was based primarily on whether they have spectroscopic confirmation, either when they were first identified or in subsequent investigations, and secondly on the published likely identification and/or evidence supplied to support a given classification.

3.2 Discovery technique

We have carefully examined the UKST H α on-band and contemporaneous broadband red continuum ‘SR’ digital image data for over...
120 deg$^2$ centred in and around the SMC. As a result we have uncovered a new population of over 50 SMC PNe candidates while also calling into doubt the veracity of some previously reported SMC PNe. Our search process adopted the same powerful and proven colour merging technique successfully applied to the LMC by Reid & Parker (2006a,b, 2013). Using the KARMA visualization software package, we surveyed 10 fields, each $\sim 4 \times 3$ in size, covering the main body and the outskirts of the galaxy. We created merged false-colour images of all ten fields, combining H$\alpha$ (coloured in blue) and broad-band (coloured in red) images. The images were then overlaid with annotation files containing the positions of all previously known 252 cross-checked EmOs of all kinds. This enabled us to easily determine the merged colour appearance of true PNe and other types of EmOs.

All 10 fields were systematically searched by visual scanning, looking for a faint, compact or barely resolved objects. By carefully choosing the image combination parameters we could perfectly balance the intensity of H$\alpha$ and broad-band red matching images. This allows only specific features of one or other pass-band to be observed, because the long 3 h H$\alpha$ exposures and short 15 min broad-band SR exposures are well matched to depth for continuum point sources. In our chosen pass-band merging scheme EmOs such as PNe and H$\alpha$ regions appear with a uniform strong blue colour, whereas normal continuum stars are a uniform pink–purple colour. Emission-line stars usually have a strong continuum component and so are easily detected by the narrow extent of their blue haloes around a strong pink core (Reid & Parker 2006a).

The RA/DEC positions of all candidates were recorded in J2000 coordinates based on the accurate WCS in our data and cross-checked for entries in SIMBAD Wenger et al. (2000) using a search radius of 1 arcmin (due to poor astrometric accuracy of early listings). If no matching astronomical object was found, the source was confirmed as a new candidate emission source. This careful scanning of our colour-merged H$\alpha$/SR imagery provided an initial sample of 67 PNe candidates. Many other new emission sources were also uncovered during this process but they are not included in this sample as they are either clearly stellar or have angular (and hence physical) extents that are large enough to rule out a PNe identification.

### 3.3 Multiwavelength images and cross-identification

PNe emission candidates uncovered by careful scrutiny of our false-colour H$\alpha$/SR imagery were cross-checked against multiwavelength data obtained from a range of other available optical, near-infrared (NIR), MIR and radio surveys, as listed in Table 2, to see if they were also detected in these data. If a PN candidate exhibited evidence of emission-line flux in at least two of our combined colour image renditions in the optical range, then it was deemed to be a corroborated candidate. These comprised our false colour H$\alpha$/SR merged images, the quotient image (H$\alpha$ divided by SR), the SuperCOSMOS broad-band ‘SSS’ blue $B_j$, red $R$ and NIR ‘$I$’-band combination or the lower resolution MCELS emission-line narrow-band combined colour image. MCELS is a deep multiple emission-line CCD survey of both Magellanic Clouds, with images in H$\alpha$, [S II] and [O III] (Smith et al. 2005). In order to allow subtraction of the stellar background and leave only emission-line objects, two MCELS continuum-band images are available. Many of our candidates were independently detected in the MCELS data but due to the faintness of many of our new candidates they are generally too faint to be seen in the SSS. Some candidates are only detected in our H$\alpha$/SR imagery but this does not rule them out as being real objects.

Our PN candidates were also cross-checked for counterparts against the Two Micron All Sky Survey (2MASS) NIR image data

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**Table 2. Multiwavelength sky surveys cross-checked.**

<table>
<thead>
<tr>
<th>Sky Survey</th>
<th>Wavelength</th>
<th>Filters</th>
<th>$\lambda_c$ (Å)</th>
<th>$\Delta\lambda$ (Å)</th>
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<tr>
<td>Optical</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MCELS (Smith et al. 2005)</td>
<td>(498–689) nm</td>
<td>H$\alpha$</td>
<td>6563</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td></td>
<td>[S II]</td>
<td>6742</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td></td>
<td>[O III]</td>
<td>5007</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Continuum-band</td>
<td>6850</td>
<td>95</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Continuum-band</td>
<td>5130</td>
<td>155</td>
</tr>
<tr>
<td>Optical and near-infrared</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SSS (Hambly et al. 2001a)</td>
<td>(400–900) nm</td>
<td>$B_j$</td>
<td>4450</td>
<td>94</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$R$</td>
<td>6580</td>
<td>1380</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$I$</td>
<td>8060</td>
<td>149</td>
</tr>
<tr>
<td>Near-infrared</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2MASS (Skrutskie et al. 2006)</td>
<td>(1.25-2.16) μm</td>
<td>J</td>
<td>1.235</td>
<td>0.162</td>
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<tr>
<td></td>
<td></td>
<td>$H$</td>
<td>1.662</td>
<td>0.251</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$K_s$</td>
<td>2.159</td>
<td>0.262</td>
</tr>
<tr>
<td>Mid-infrared</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WISE (Wright et al. 2010)</td>
<td>(3.4-22) μm</td>
<td>W1</td>
<td>3.35</td>
<td>0.66</td>
</tr>
<tr>
<td></td>
<td></td>
<td>W2</td>
<td>4.60</td>
<td>1.04</td>
</tr>
<tr>
<td></td>
<td></td>
<td>W3</td>
<td>11.56</td>
<td>5.51</td>
</tr>
<tr>
<td></td>
<td></td>
<td>W4</td>
<td>22.09</td>
<td>4.10</td>
</tr>
<tr>
<td>Radio</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MGPS2 (Green 2002)</td>
<td>~35.6 cm</td>
<td>0</td>
<td>–</td>
<td>–</td>
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</table>
and the sensitive but lower resolution Wide-field Infrared Survey Explorer (WISE) MIR imagery, Wright et al. (2010) at 3.4, 4.6, 12 and 22 μm (bands named W1 to W4) and the Molonglo Galactic Plane Survey 2nd Epoch (MGPS2) 843-MHz radio images. These data can provide additional diagnostic power in cases where multiple detections are made e.g. Parker et al. (2012), allowing many mimics in previous compilations to be identified.

PNets tend to have a narrow-range of distinctive appearance in false-colour images from different surveys that can assist identification. For example, Cohen et al. (2007) have shown that the dominant colours of PNets in their study of Spitzer MIR imagery are red, orange and violet when combining the different MIR bands as false-colour RGB images. The dominant colours of PNets in Supercosmos Sky Survey (SSS) RGB images are green or turquoise due to the significant contribution from the strong [O III] PN emission line and/or the Hα/[N II] lines in the red band.

Following this careful cross-check we narrowed the list to 50 high-quality PN candidates by excluding objects that did not appear in any of these other surveys and that also had other image characteristics that indicated they were possible artefacts or plate flaws in the Hα/IR data. We selected four candidates for initial spectroscopic follow-up during a brief window of opportunity in another of our observing runs. The effectiveness of our multiwavelength selection technique to deliver high-quality PN candidates was shown by the subsequent spectroscopic PN confirmation of all four preliminary targets (100% per cent success). This is perhaps unsurprising given the equivalent high success rate for PN confirmation in the LMC by Reid & Parker (2006a,b) who used almost identical selection technique. Fig. 1 displays false colour Hα/IR band and quotient discovery images of these candidates, together with the SSS I, R and B combined RGB images. Only the first and brightest of our new PNets, DPR1, has a clear SSS counterpart though very faint detections of the others are seen. This source is also just visible in MCELS but not at the level were its emission nature would have been obvious. The adopted naming scheme for our new PNets follows our usual process of using the surname initial of the key people involved in the project – here the first three authors (PhD student and two supervisors).

4 SPECTROSCOPIC CONFIRMATION

Four PN candidates from our new compilation named DPR1 to DPR4 were observed by one of us (QAP) using the Cassegrain spectrograph on the South African Astronomical Observatory’s (SAAO) 1.9 m Radcliffe telescope over a five night period in 2014 March in order to test the efficacy of our selection process. The standard slit-spectrograph was used with a SITe 266 × 1798 pixel CCD giving 0.5 arcsec pixel−1 on the slit with a slit scale of 6 arcsec mm−1. It was used with low resolution grating ‘7’ (300 lines mm−1 with 5 Å resolution and dispersion of 210 Å mm−1) at an angle of 17° 24′. This provides a broad spectral range from 3500 to 7400 Å which covers all the strongest PN optical emission lines for a dispersion of 1.8 Å pixel−1.

Appropriate bias frames, arc calibration exposures, dome and twilight flat-fields and radial velocity and spectrophotometric standard stars were taken to assist with the standard spectral reduction, flux calibration and quality control process. For DPR1, DPR2 and DPR4 the slit width was 2 arcsec. For the more resolved candidate DPR3 a 3 arcsec slit was used to capture more of the object’s flux at the expense of a modest reduction in spectroscopic resolution due to the poorer seeing during this exposure. For all targets, the same spectrophotometric standard star LTT3864 was observed.

Exposures were carefully reduced with the Image Reduction and Analysis Facility (IRAF) V2.161 (Tody 1986, 1993) following standard procedures. These steps include frame trimming, average bias frame subtraction, dome and twilight flat-fielding, cosmic ray removal, 1D spectral extraction, wavelength calibration, sky subtraction and flux calibration. The observing conditions were generally stable and the slit width was adjusted according to the seeing conditions and in the case of spectrophotometric standard star LTT3864, widened to 5 arcsec to ensure all flux was collected.

Each observed candidate was confirmed as an emission-line source and exhibited no obvious stellar continuum. This eliminates confusion with any emission-line star for the two compact sources DPR1 and DPR4. Each candidate also gave high ratios of [N II] to Hα that are not observed in H II regions, which are the most likely narrow-emission-line contaminant (Kennicutt et al. 2000). Unfortunately, none of the spectra appear to exhibit the [O III] or Hβ emission lines in the blue. This indicates the possible effects of some modest extinction but more seriously the limited blue S/N obtained for these faint sources, especially for the more clearly resolved and lower surface-brightness candidates DPR2 and DPR3.

The applied flux calibration is indicative only but measured line ratios should be quite reliable in principle due to the close wavelength proximity of the lines used, modulo the effects of low S/N for DPR2 and DPR3. The spectra of newly discovered PN candidates are shown in Fig. 2. A summary of observed line ratios (and errors), radial velocities and estimated angular and physical size for these new PN candidates is given in Table 3. A discussion of the results of each observed candidate is given below.

4.1 DPR1

The spectrum of this compact, unresolved PN candidate DPR1 is of reasonable S/N and exhibits no stellar continuum and only narrow-lined Hα λ6563 Å emission and very strong [N II]λ6548, 6584 Å lines. There are no evident [O III] or Hβ lines in the blue or clear detection of [S II] in the red. The red emission lines effectively rule out confusion with any emission-line star or compact H II region. For more accurate line ratio determination and possible detection of fainter emission lines we intend to re-observe all four candidates on a larger telescope.

The sky spectrum was well determined for this object because the angular size of the target was much smaller than the length of the spectrograph slit which provides ample adjacent sky regions. This is seen by the lack any residual presence of the very strong [O I] night sky line at 5577 Å and also the lack of residuals from the weaker [O I] 6363 Å line and only a small residual from the stronger 6300 Å line in the red. Hence, one can be confident that the observed, low Hα emission is real and not due to an over subtracted H α sky component. In such low-resolution spectra the observed auroral component at effectively zero velocity and that expected for a PN in the SMC of ~160 km s−1 will not present much of an offset.

Furthermore, any Galactic Hα emission component would be very weak at this Galactic latitude (∼44°) while an examination of Fig. 1 indicates absence of any local diffuse SMC emission component. De-blended Gaussian fits were applied to the closely spaced [N II] and Hα emission lines to provide radial velocity estimates

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1 IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy (AURA) under a cooperative agreement with the National Science Foundation.
and relative line fluxes for measuring the line ratios. A large velocity gradient for different object types is observed in the SMC, ranging from 90 to 200 km s$^{-1}$, as shown by Torres & Carranza (1987) and Stanimirović, Staveley-Smith & Jones (2004). The DPR1 lines provide an average radial velocity of $\langle V_r \rangle = 80$ km s$^{-1}$, $\sigma_n = 10$ km s$^{-1}$ and $n = 3$ (including heliocentric velocity correction) which is little low for membership of the SMC. On the basis of our combined imaging and new spectroscopic evidence we identify DPR1 as a likely type I PNe, largely due to the very high [N II]/H $\alpha$ ratio of 7.0 and weak/absent [S II]. Without measurable [O III] lines in the spectrum this object likely falls into the low excitation category but the absence of detectable H $\beta$ also indicates the effects of poor S/N in the blue.

4.2 DPR2 and DPR3

These two low-surface-brightness candidates are clearly resolved as can be seen in their quotient images in Fig. 1, with major axes of 7.5 and 4.5 arcsec, respectively (determined from FWHM of the brightness profile), eliminating any possible confusion with emission-line
Figure 2. SAAO spectra of newly discovered PNe in the SMC. Top left: low excitation nebula DPR1 with observed high [N II]/Hα ratio. Note the absence of [O III] emission lines. Top right: low signal-to-noise ratio (S/N) spectra of low excitation nebula DPR2. Some artefacts of airglow processing remain, but nebula [N II] and Hα emission are discernible above the general background noise. Bottom left: low (S/N) spectra of low excitation nebula DPR3. Airglow processing artefacts again remain, but nebula Hα and [N II] emission is discernible. Bottom right: low excitation nebula DPR4, again with a high [N II]/Hα ratio, similar to DPR1. In common with other candidates, [O III] lines are not detected.

Table 3. Observing log of spectroscopically confirmed new PNe candidates towards the SMC with observed spectroscopic relative line intensity (F) ratios, their radial velocities, angular and physical sizes.

<table>
<thead>
<tr>
<th>Name</th>
<th>RA (h m s)</th>
<th>Dec (°’’’)</th>
<th>Date</th>
<th>Time (UT)</th>
<th>$T_{\text{exp}}$ (s)</th>
<th>F [N II]/F Hα</th>
<th>$\langle V_r \rangle$ (km s$^{-1}$)</th>
<th>$\sigma_n$ (km s$^{-1}$)</th>
<th>$\Theta_{\text{arcsec}}$</th>
<th>$d$ (pc)</th>
<th>Seeing (arcsec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DPR1</td>
<td>00 54 26.00</td>
<td>−72 30 59.4</td>
<td>7 Mar 2014</td>
<td>17:52:42</td>
<td>1200</td>
<td>7.0±0.64</td>
<td>80</td>
<td>10</td>
<td>Unresolved</td>
<td>–</td>
<td>2.2</td>
</tr>
<tr>
<td>DPR2</td>
<td>00 59 47.60</td>
<td>−72 32 31.4</td>
<td>11 Mar 2014</td>
<td>18:01:46</td>
<td>1130</td>
<td>2.2±0.80</td>
<td>169</td>
<td>4.5</td>
<td>7.5</td>
<td>2.2</td>
<td>2.9</td>
</tr>
<tr>
<td>DPR3</td>
<td>01 02 55.20</td>
<td>−72 21 32.0</td>
<td>9 Mar 2014</td>
<td>18:00:10</td>
<td>1800</td>
<td>3.7±1.00</td>
<td>241</td>
<td>16</td>
<td>4.5</td>
<td>1.3</td>
<td>2.4</td>
</tr>
<tr>
<td>DPR4</td>
<td>01 04 30.00</td>
<td>−73 15 10.5</td>
<td>8 Mar 2014</td>
<td>17:59:24</td>
<td>1200</td>
<td>7.7±0.75</td>
<td>167</td>
<td>18.5</td>
<td>Unresolved</td>
<td>–</td>
<td>2.5</td>
</tr>
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</table>

stars. At the nominal distance of the SMC this corresponds to maximum physical sizes of 2.2 and 1.3 pc (with seeing estimated at 2.5 arcsec) which are at the upper size limit for Galactic PN. For example, Frew, Parker & Russell (2006) reported discovery of two highly evolved Galactic PNe, RCW24 and RCW69, with physical dimensions larger than 5 pc and 1.3 pc, respectively, while Pierce et al. (2004) reported PFP1 with diameter of ∼1.5 pc.

Confusion with young SNRs is also ruled out by the absence of any strong [S II] and hence shocked conditions. Their observed spectra, although noisy, are also very similar. Both have high [N II]/Hα ratios of between 2 and 3 – still well in excess of that exhibited by H II regions. A PN identification for both sources is consequently strongly favoured. Gaussian line de-blending was carefully applied to the closely spaced [N II], Hα emission lines to provide radial velocity estimates and relative line fluxes for measuring the line ratios which in these two cases have larger associated errors. The measured radial velocity for DPR2 is $\langle V_r \rangle = 169$ km s$^{-1}$, $\sigma_n = 4.5$ km s$^{-1}$, $n = 3$ and for DPR3 is $\langle V_r \rangle = 241$ km s$^{-1}$, $\sigma_n = 16$ km s$^{-1}$, $n = 3$, both with heliocentric velocity correction applied. The result for DPR2 is in excellent agreement with the SMC velocity within the errors while that for DPR3 is about 50 km s$^{-1}$ high.

Artifacts from night sky-subtraction due to low S/N are present, with contributions from [O I] λλ5577, 6300, 6364 Å. These are removed from the spectra for these two cases so the PN emission lines are easier to see. Improved S/N on a large aperture telescope is needed to provide other plasma diagnostics as well as the ability to work out extinction directly from the Balmer decrement. The imaging and spectroscopic evidence collected nonetheless strongly
Four new planetary nebulae towards the SMC

Figure 3. SMC MCELS mosaic Hα image with positions of 96 known PNe (confirmed and candidates) (small red circles), 46 new candidates (green circles) and 4 new PNe confirmed in this study (large blue circles).

support assessment of DPR2 and DPR3 as PNe. They are also likely highly evolved, low-excitation type I PNe given the observed [N II]/Hα ratios and sizes but the poor S/N prevents detection of Hβ or any [O III] lines.

4.3 DPR4

The spectrum of our final candidate DPR4, another compact object, has reasonable S/N and exhibits strong [N II] emission similar to DPR1. Again there is the absence of any obvious [O III] or Hβ lines in the blue likely due to low S/N given the strength of Hβ. Only Hα and [N II]λλ6548, 6584 Å lines are present, with the observed [N II]/Hα ratio of 7.7, the highest of all four candidates. Confusion with compact H II regions or emission-line stars are ruled out by the observed narrow lines ratios and the absence of any stellar continuum. Again sky subtraction is excellent with no residual [O I] at 5577, 6300, 6363 Å being evident and this process does not contribute to any oversubtraction of Hα, while Fig. 1 also shows an absence of any local SMC diffuse Hα emission component.

De-blended Gaussian fits were applied to the [N II], Hα, [N II] lines to permit radial velocity estimation and to provide the relative fluxes for the line ratio measurement. The average radial velocity obtained from these lines, including application of the appropriate heliocentric velocity correction, was \( \langle V_r \rangle = 167 \text{ km s}^{-1} \), \( \sigma = 18.5 \text{ km s}^{-1} \) in excellent agreement with the canonical SMC radial velocity. As for previous candidates, re-observation of DPR4 is recommended under better observing conditions and on a larger telescope. Our imaging and spectroscopic data strongly support assessment of this candidate as another low excitation likely type I PN.

5 DISCUSSION AND CONCLUSIONS

We have undertaken a survey for faint PNe in the SMC based on careful examination of deep, arcsecond resolution, UKST Hα
exhibit strong [N II] emission and weak to absent [O III] emission. These all resemble Galactic PNe similar to the new SMC PNe uncovered here.

The positions of all emission sources uncovered were also cross-checked against existing PNe catalogues and general SMC EmOs compilations for previous detections. This enabled the identification of 50 new PN candidates. Four of these were selected for preliminary spectroscopic follow-up and all were subsequently confirmed as bona fide PNe. The positions of all our newly discovered candidates are shown in Fig. 3 which gives the SMC MCELS H α mosaic image overlaid with the positions of the 96 currently known SMC PNe (spectroscopically confirmed as candidates) as red circles, our 46 new candidates as green circles and the 4 new PNe confirmed in this study as blue circles.

The confirmatory spectra for these candidates are all somewhat homogenous. Their observed [N II]/H α line ratios are all very high ranging from 2 to 7. This rules out any possible confusion with H II regions which never show such ratios, while other spectral features exclude confusion with SNRs (absence of any [S II] lines) or emission-line stars (only narrow lines and absence of any continuum). Galactic PNe similar to the new SMC PNe uncovered here include the evolved PNe IsWe 1, RCW 24 and WeDe 1. These all exhibit strong [N II] emission and weak to absent [O III] emission.

Based on these preliminary results, we expect to increase the number of SMC PNe by between 20 and 50 per cent after planned spectroscopic follow-up of all of our PN candidates and refinement of source identifications of existing SMC emission-line catalogues. This work will include multiwavelength analysis and spectroscopic confirmation (or rejection) of SMC EmOs previously listed as PNe.

**ACKNOWLEDGEMENTS**

We thank the anonymous referee who provided valuable and detailed comments which have significantly improved the quality of the paper. Financial support for this research was provided by Macquarie University Research Excellence Scholarship. Danica Drašković would also like to thank Macquarie University for a PhD scholarship. We thank South African Astronomical Observatory for observing time. We also thank Dr David Frew for useful discussions and Mr Travis Stenborg for help with the SAAO observations. This research has made use of the SIMBAD database, operated at CDS, Strasbourg, France.

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