RADIO PLANETARY NEBULAE IN THE MAGELLANIC CLOUDS

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ABSTRACT

Comparison of recent Australia Telescope Compact Array (ATCA) / Parkes mosaic surveys of the Magellanic Clouds (MCs) with positions of known planetary nebulae (PNe) have revealed a total of 29 new radio counterparts. Six (6) Small Magellanic Cloud (SMC) candidates were found in 1.42 and 2.37 GHz mosaics, while 23 were found in the Large Magellanic Cloud (LMC) at 1.377 GHz. Followup high resolution ATCA observations at 6 and 3 cm (4″and 2″ beams, respectively) reveal that these extended sources are located within 2″ of their optical counterparts with higher than expected flux densities. Complimentary optical PNe spectra have typical electron temperatures and densities. Estimates of nebular ionized mass, based on these elevated radio flux densities, suggest they may be the result of significant circumstellar envelopes. These envelopes may have been formed from winds ejected from high mass (up to 8 $M_\odot$) progenitor stars.

INTRODUCTION

Ninety five percent of all stars that evolve from the main sequence will end their lives as white dwarfs. Planetary nebulae (PNe) are thought to represent a short (10^4 yr) phase between the asymptotic giant branch (AGB) and white dwarfs. The central stars are remnants of the electron-degenerate C-O cores of their AGB progenitors, having lost most of their H envelopes from mass loss on the AGB (Kwok 2005). PNe possess ionized, neutral atomic, molecular and solid states of matter in diverse regions with different temperature, density and morphological structure. Their physical environments range in temperature from 10^2 K to greater than 10^6 K and they radiate from the X-ray to the radio.

Most PNe have central-star and nebular masses of only about 0.6 and 0.3 $M_\odot$, respectively. However, detection of white dwarfs in open clusters suggests the main-sequence mass of PNe progenitors can be as high as 8 $M_\odot$ (Kwok 1994). If a high rate of mass loss continues for an extended fraction of the AGB's lifetime, a significant fraction of a star's mass can be built up around the star, forming a circumstellar envelope (CSE). If the transition from the AGB to PN stage is short, then such CSEs could have a significant effect on the formation of PNe, resulting in the detection of optical AGB haloes. The presence of these haloes have been known since the 1930s (Duncan 1937).

Corradi et al. (2003) summarizes a 'standard' spherical PN model that includes an evolving, hot, central stellar remnant whereby the combined action of photoionization and wind interaction causes the formation of a double-shell inner nebula. Optically, this is composed of a bright inner rim, the result of the interaction of the post-AGB wind with the slow AGB one; and an outer fainter shell which is set up by photoionization during the early stages of evolution. Around this inner double-shell nebula is the location of the large photoionized halo described above having on average, a surface brightness 10^3 times fainter than that of both inner rim and shell. Its inner edge is the signature of the last thermal pulse on the AGB.

Optical spectral requirements for the confirmation of PNe have been summarised very nicely by Reid & Parker (2006). Classically, PNe can be identified by a [O III] 5007Å:[O III] 4959Å:Hβ 4861Å intensity ratio near 9:3:1. However, this can be relaxed when [N II] 6583Å is greater than Hα. In that case, a strong [O III] line has been often detected along with the high excitation He II 4686Å line hardly seen in H II regions. Generally, the [O II] 3727Å doublet is seen in PNe, as well as [Ne III] 3869Å, [Ar III] 7135Å and He I 6678Å lines. [S II] 6717, 6731Å is usually present but not significant when compared to Hα.

Distance estimates to most Galactic PNe are generally poor. Most known PNe are weak thermal radio sources and although morphologies of these radio objects are similar to their optical counterparts, radio interferometric observations allow us to image the structure of a PN's ionized component. A spherically symmetric uniform density PN has an ionized mass, M_i, that can be expressed as:

$$M_i = 282(D_{kpc})^2 F_5 (n_e)^{-1} M_\odot, \tag{1}$$

where D_{kpc} is distance (kpc), F_5 is radio flux density at 5 GHz (Jy) and n_e represents electron density (cm^{-3}) derived from forbidden-line ratios (Kwok 2000). In cases where the PN distance is unknown, this equation can be inverted to provide a useful distance estimate.

Study of extragalactic radio PNe have the advantage that their distance is known with much greater certainty than Galactic PNe. Centimeter radio emission from PNe also can be used to estimate interstellar extinction by comparing radio and optical Balmer-line fluxes (Luo et al. 2005). The study of radio PNe at a known distance allows us to better understand the properties of PNe in our own Galaxy, and ultimately to refine methods of estimating their distances.

Planetary nebulae within the MCs should not have measurable radio emission much above the sensitivity limits of our data. For example, the Galactic PN G313.3+00.3 (regarded as one of the luminous in the Galaxy; Cohen et al. 2005) would have flux densities of 0.6 and 0.4 mJy at 1.384 and 2.496 GHz at the distance of the LMC. Zijlstra et al. (1994) has reported a radio [WC]-type planetary nebula in the LMC named SMP L58 (Sanduleak et al. 1978) having flux densities of 0.6 and 1.1 mJy at 3 and 6 cm. However, we did not detect SMP L58 in any of our LMC mosaic radio surveys. This reflects the difficulty of radio observations of these extragalactic PNe.

INITIAL OBSERVATIONS

In the past decade, several ATCA moderate resolution surveys of the Magellanic Clouds (MCs) have been completed. Deep ATCA+Parkes radio-continuum surveys of the Small Magellanic Cloud (SMC) were conducted at 1.42 and 2.37 GHz, with supplemental snap-shot images at 4.80 and 8.64 GHz, achieving sensitivities of 1.8, 0.4, 0.8 and 0.4 mJy beam^{-1} respectively (Filipović 2002). The maps have angular resolutions of 98″, 40″, 30″ and 15″. The surveys at 1.42 and 2.37 GHz were conducted in mosaic mode with over 320 separate pointings using 5 antennae in the 375 m array configuration. To recover information on larger scales, the ATCA mosaic data were combined with single-dish data from the Parkes radio-telescope. In addition, new complete mosaics of the SMC at 4.80 and 8.64 GHz have recently been completed by J. Dickel.

For the Large Magellanic Cloud (LMC), a new moderate resolution (40″; sensitivity $\sim$ 0.3 mJy beam^{-1}) ATCA+Parkes survey at 1.377 GHz (λ = 20 cm) (Hughes in prep.) complements ATCA+Parkes mosaic images at 4.8 and 8.64 GHz obtained by Dickel et al. (2005). Dickel's 4.8 GHz total intensity image has a FWHM of 33″ while the 8.64 GHz image has a FWHM of 20″. Both have sensitivities of $\sim$ 0.3 mJy beam^{-1} and the positional certainties for all three radio continuum maps of the LMC are less than 1″.

MULTI-WAVELENGTH CO-IDENTIFICATIONS

The radio-continuum surveys were searched within 5″ of known optical PNe for co-identifications. In the SMC, PNe lists given by Morgan (1995) (their Table 3) and Jacoby & DeMarco (2002) (their Table 4), contain a total of 139 PNe. We found four radio candidates that were spatially coincident with the PNe JD04, JD10, JD26 and JD28. (We refer to these PNe using the names listed in Jacoby & DeMarco 2002). Two additional sources have been identified by P. F. Winkler, bringing the total to six (6).

Within the LMC, we found 23 co-identifications using optical PNe catalogues presented by Leisy et al. (1997) and Reid & Parker (2006). The catalogue by Leisy et al. (1997) contain accurate positions and finding charts for $\sim$ 280 LMC PNe from all major surveys previous to 1997. A recent 'complete' catalogue presented by Reid & Parker (2006) identify $\sim$ 629 LMC PNe. Results of our searches for radio PNe and their estimated ionized masses (M_i), using Eqn. 1, are given in Table 1.

In addition to the ATCA+Parkes surveys, we searched the 843 MHz Sydney University Molonglo Sky Survey (SUMSS; resolution $\sim$ 45″, sensitivity $\sim$ 1 mJy) for co-incident sources (Bock et al. 1999). Here we find two SMC sources with measurable flux densities and place limits on two additional ones. In the LMC, we find 9 co-incident sources and place limits on eight more. In the optical, high resolution imaging and spectra from a recent Hubble Space Telescope (HST) survey of 59 PNe in the MCs (Shaw et al. 2006) have 8 radio PNe candidate matches.

TABLE 1: Result of searches for radio PNe candidates in the MCs. ΔP is the positional difference between radio and optical sources.

SMC

No.	ATCA Radio Source Name	Optical PN Name	ΔP (arcsec)	M_i ($M_\odot$)	No.	ATCA Radio Source Name	Optical PN Name	ΔP (arcsec)	M_i ($M_\odot$)
1	J004336-730227	JD04	1″	2.7	4	J004836-725802	JD10	2″	2.7
2	J004808-731454	Winkler	1″	16.8	5	J005730-723224	JD26	2″	3.1
3	J004818-730557	Winkler	1″		6	J005842-722716	JD28	1″	4.7

LMC

No.	ATCA Radio Source Name	Optical PN Name	ΔP (arcsec)	M_i ($M_\odot$)	No.	ATCA Radio Source Name	Optical PN Name	ΔP (arcsec)	M_i ($M_\odot$)
1	J045013-693353	SMP L8	4″	–	13	J052249-664056	RP 1113	1″	4.2
2	J045424-692942	RP1716	< 1″	6.9	14	J052425-693906	RP 872	5″	–
3	J050447-664030	RP1933	1″	8.5	15	J052455-713255	SMP L62	5″	1.5
4	J050624-690320	SMP L25	3″	1.5	16	J053054-683422	RP 993	< 1″	8.8
5	J051009-682955	SMP L33	3″	–	17	J053328-715227	SMP L74	5″	–
6	J051142-683459	SMP L39	2″	–	18	J053346-683648	SMP L75	5″	–
7	J051906-682136	RP 1495	2″	7.1	19	J053620-671807	SMP L83	< 1″	0.6
8	J051918-694718	RP 2194	1″	9.3	20	J053653-715339	SMP L84	4″	–
9	J051954-693104	SMP L47	2″	1.5	21	J053706-694717	RP 641	2″	–
10	J052009-695339	SMP L48	1″	0.8	22	J054045-702805	RP 105	< 1″	5.9
11	J052129-675107	RP 1541	1″	0.5	23	J054237-700930	SMP L89	3″	–
12	J052129-675107	RP 1534	1″	6.9					

Based on image size, PNe size, positional accuracy, resolution and number of detected sources found at given frequency, we estimate a chance coincidence of a radio match to a known PN in the SMC 2.37 GHz image to be 1 in 226,979. We also employed a 'shift technique' in order to estimate the possibility of false detections. For this, we moved the position of known optical PNe by 30′ in four directions (RA and Dec) and counted the number of spurious identifications. We find only one false detection, implying that only one or two of the 29 cross-identifications that we report here occurred by chance.

FOLLOWUP OBSERVATIONS

Ongoing followup ATCA observations at 6 and 3 cm give much higher resolutions (4″ and 2″, respectively) and appear to confirm these objects as bright radio counterparts to within 2″ of known optical PNe (see Fig. 1). The number and flux densities (up to ten times greater than expected) of these candidate radio PNe are unexpected, given the distances of the SMC ($\sim$ 60.6 kpc; Hilditch et al. 2005) and LMC ($\sim$ 50.1 kpc; Alves 2004). This may well modify our current understanding of PNe, including their progenitor mass and evolution.

Long-slit spectral observations were conducted January 2008, using the 1.9-meter telescope and Cassegrain spectrograph at the South African Astronomical Observatory (SAAO) in Sutherland. We used grating number 7 (300 lpmm) to obtain spectra between 3500 and 6200 Å having a resolution of 5 Å.

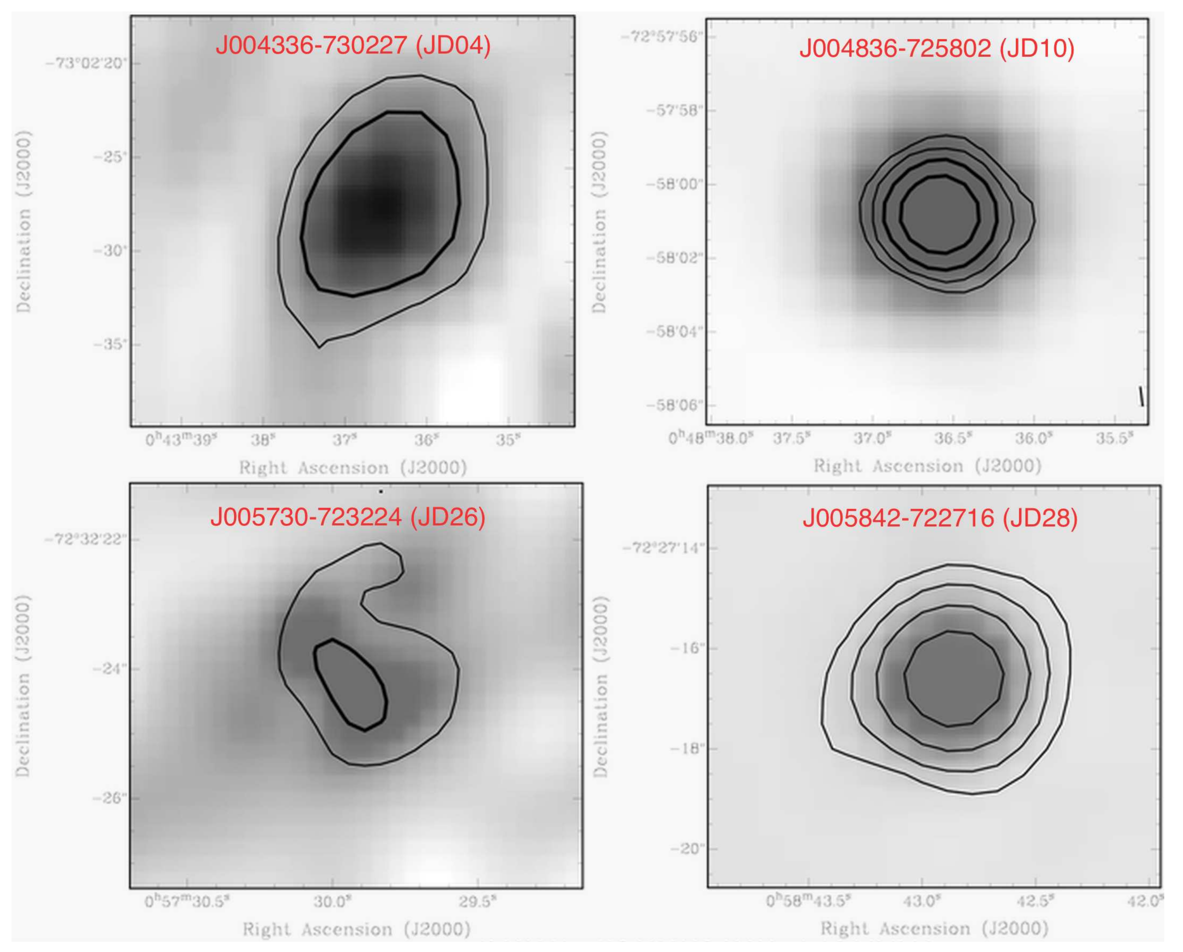

FIGURE 1: Images and contours of four SMC radio PNe candidates. J004336-730227 (JD04) shows image and contours at 20 cm (beam = 7″ × 8″) while the remainder have 6 cm (beam = 4″) images superimposed with 3 cm (beam = 2″) contours.

Spectrograph exposure times were limited to 800 s with a positional accuracy of < 1″. Data reduction included bias subtraction and flat-field correction using the IRAF software package. One-dimensional spectra was wavelength calibrated using standard lines from a CuAr arc and flux calibration was applied using the spectrometric standard star EG 21. Observing conditions were not photometric and seeing was limited to an arcsecond at best, but varied throughout the evening. In general, the spectra confirm these objects as PNe having typical nebular temperatures; selected spectra that correspond to objects in Fig. 1 are shown in Fig. 2.

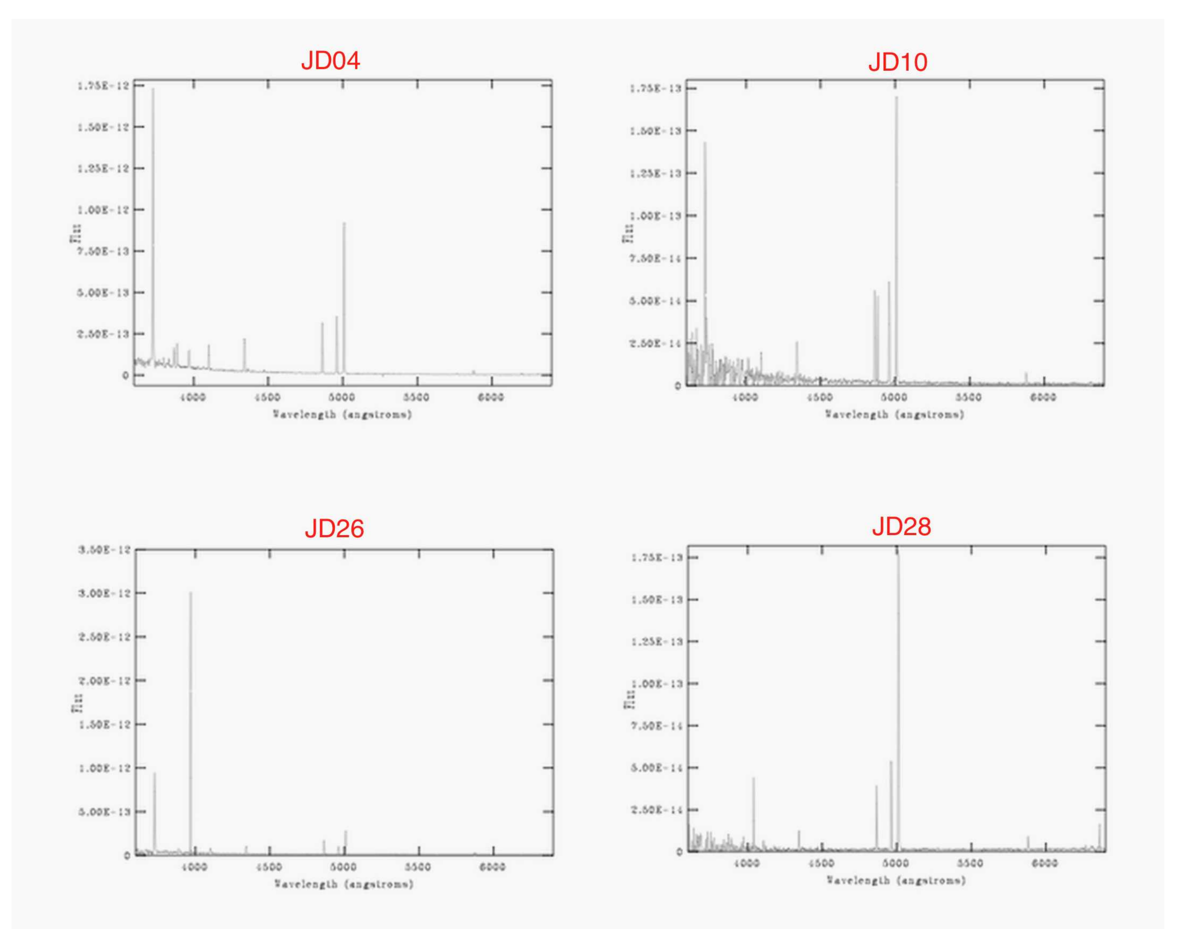

FIGURE 2: Selected long-slit spectra (3500–6200 Å) of optical PNe co-identified with radio sources shown in Fig. 1.

CONCLUSIONS

We have identified radio counterparts to 29 known PNe within the MCs. These radio PNe candidates are brighter than expected, based on distances to the clouds and represent about 4 percent of the optical MC PNe population. Based on the ionized masses of these nebulae, we suggest they represent a subpopulation of stars with higher masses (up to 8 $M_\odot$). This mass is lost due to winds which form double-shells and ABG halos prior to the PNe stage.

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