Spectroscopy of two PN candidates in IC 10

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ABSTRACT

We present the results of the first spectroscopic observations of two planetary nebulae (PN) candidates in the Local Group dwarf irregular galaxy IC 10. Using several spectral classification diagrams we show that the brightest PN candidate (PN 7) is not a PN, but rather a compact H II region consisting of two components with low electron number densities. After the rejection of this PN candidate, the IC 10 planetary nebula luminosity function cutoff becomes very close to the standard value. With the compiled spectroscopic data for a large number of extragalactic PNe, we analyse a series of diagnostic diagrams to generate quantitative criteria for separating PNe from unresolved H II regions. We show that, with the help of the diagnostic diagrams and the derived set of criteria, PNe can be distinguished from H II regions with an efficiency of ∼99.6%. With the obtained spectroscopic data we confirm that another, fainter PN candidate (PN 9) is a genuine PN. We argue that, based on all currently available PNe data, IC 10 is located at a distance 725±63 kpc (distance modulus (m − M) = 24.30±0.18).

Key words: ISM: planetary nebulae — galaxies: irregular — galaxies: evolution — galaxies: individual: IC 10 — Local Group

1 INTRODUCTION

The Local Group is an excellent laboratory for studies of galaxy evolution, providing us with a wide range of different galaxy types in a variety of environments. The star formation (SF) histories of Local Group galaxies can be obtained from color-magnitude diagrams of resolved stars (e.g., Aparicio & Gallart 1995). Using this method it is possible to constrain the entire SF and chemical enrichment history of galaxies. However, the results are model-dependent, and should be compared with other, additional observational data which can be obtained for Local Group galaxies. One such complementary means of determining the SF and chemical evolution histories is a study of planetary nebulae (PNe), which can be used simultaneously as age, kinematics and metallicity tracers. The abundances from both H II regions and PNe allow one to derive an approximate enrichment history for a galaxy from intermediate ages to the present day and permit abundance measurements at different locations. The latter, in turn, helps to test the homogeneity with which elements are distributed through a galaxy and, thus, the timescale for heavy element diffusion and mixing (Kniazev et al. 2005a, 2006a; Magrini et al. 2005a).

In this paper, we present new results of a PN study in the Local Group dwarf irregular galaxy IC 10, which is situated at low Galactic latitude (b = −3° 3). Estimates of the distance to IC 10 vary, including values of 830±110 kpc, based on observations of Cepheids (Saha et al. 1996); 660±66 kpc, based on Cepheids and tip of the red giant branch (RGB) stars (Sakai et al. 1999); and 741±37 kpc, based on a study of carbon stars (Demers et al. 2004). IC 10 is highly obscured, with E(B−V) = 0.77 ± 0.07 (Richer et al. 2001). With the position of IC 10 on the sky only 18° apart from M31, van den Bergh (2000) suggests that it may be a member of the M31 subgroup. The large number of H II regions (Hodge & Lee 1990) indicates that IC 10 is undergoing a massive episode of SF. Estimates of the intensity of SF were revised upward after many WR stars were discovered in IC 10 (Massey & Armandroff 1992; Massey & Armandroff 1993). This number of WR stars is remarkable for a galaxy of its size and is at least a factor of two higher than the density of such stars seen in any other Local Group galaxy. This fact led Massey & Armandroff (1993) to classify IC 10 as a starburst galaxy, the only such object in the Local Group.
Richer et al. (2001) concluded that IC 10 should be considered a blue compact dwarf galaxy.

Sixteen PN candidates were identified in IC 10 by Magrini et al. (2003b) on the basis of both [O\textsc{iii}] and H\textalpha+[N\textsc{ii}] continuum-subtracted images. No PNe were found very close to the center of this galaxy, presumably because of the presence of numerous extended HII regions covering a large fraction of the galaxy’s area. The distribution of m\textsubscript{5007} magnitudes for all detected PN candidates looks unusual since the brightest one is \sim1.7 brighter than the next brightest. Observations and analysis of three of these PN candidates are presented below.

The paper is organized as follows. Section 2 gives a description of all observations and the data reduction. Our results are summarized in Section 3 and discussed in Section 4. Throughout the paper, for distance-dependent parameters we have assumed a distance to IC 10 of 740 kpc (Demers et al. 2004).

2 SPECTRAL OBSERVATIONS AND DATA REDUCTION

Long-slit spectral observations were obtained with the SCORPIO multi-mode instrument (Afanasiev & Moiseev 2005) installed in the prime focus of the SAO 6 m telescope (BTA), during two nights in November 2004. The VPH550 grism was used with the 2K×2K CCD detector EEV 42-40, with an exposed region of 2048×600 px. This gave a wavelength range \sim3500–7500 \AA with \sim2.0 \AA pixel\(^{-1}\) and FWHM \sim12 \AA along the dispersion direction. The scale along the slit was 0.18 pixel\(^{-1}\), with a total length of \sim2’ and a slit width of 1’’. The coordinates for the observed PN candidates were taken from Magrini et al. (2003b). H\textalpha acquisition images were obtained before the spectroscopic observations in order to select optimal positions for the slit. In these images, the candidate PN 7 (\(\alpha\text{2000.0} = 00:20:22.22, \delta\text{2000.0} = 59:20:01.6\) from Magrini et al. (2003b)) appeared as an elongated object consisting of two regions: a starlike one (hereafter PN 7a) and an extended one (hereafter PN 7b). The slit was positioned to observe both of these simultaneously. Candidate PN 9 (\(\alpha\text{2000.0} = 00:20:32.08, \delta\text{2000.0} = 59:16:01.6\)) is a starlike source. Finding charts and the slit positions for our observations are shown in Figure 1. The exposure times used were 2×15 min for PN 7 and 2×20 min for PN 9, and the candidates were observed at airmasses of 1.8 and 1.1 respectively. For wavelength calibration, the object spectra were complemented by reference He–Ne–Ar lamp spectra. Bias and flat-field images were also acquired for a standard reduction of 2D spectra. The spectrophotometric standard star Feige 34 (Bohlin 1996) was observed for flux calibration.

Reduction of all data was performed using the standard reduction systems MIDAS\(^1\) and IRAF\(^2\). All cosmic ray hits were removed within MIDAS, while the IRAF package CCDRED was used for bad pixel removal, trimming, bias-dark subtraction, slit profile and flat-field corrections. To achieve accurate wavelength calibration, correction for distortion and tilt for each frame, sky subtraction and the correction for atmospheric extinction, the IRAF package LONGSLIT was used. Then, using the data on the spectrophotometric standard star, each 2D spectrum was transformed to absolute fluxes and one-dimensional spectra were extracted to obtain the total observed emission line fluxes.

All emission lines were measured using the MIDAS pro-

\(^1\) MIDAS is the acronym for the European Southern Observatory package – Munich Image Data Analysis System.

\(^2\) The Image Reduction and Analysis Facility is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
grams described by Kniazev et al. (2004). Briefly, they measure the continuum with the method of Shergin et al. (1996), derive robust noise estimates, and fit resolved lines with a single Gaussian superimposed on the continuum-subtracted spectrum. Some emission lines which were not sufficiently separated at the given spectral resolution were fitted simultaneously as a blend of two or three Gaussian features. They include the Hα λ6563 and [N ii] λλ6548,6584 lines and the [S ii] λλ6716,6731 lines. The quoted errors of single line intensities include the following components: (1) errors related to the Poisson statistics of line photon flux; (2) the error resulting from the measurement of the underlying continuum, which gives the dominant contribution to the errors on faint lines; (3) an additional error related to the goodness of fit for fluxes of blended lines; and (4) a term related to the uncertainty in the spectral sensitivity curve (5% for the presented observations), which constitutes the main contribution to the errors of the relative intensities of strong lines. All these components are added in quadrature, and the total errors have been propagated to calculate the errors of all subsequently derived parameters.

3 RESULTS

The relative intensities (normalised to I(Hβ)) of all measured emission lines, as well as the derived extinction coefficient C(Hβ), the equivalent widths (EWs) of Balmer absorption lines, the measured flux of the Hβ emission line, the measured heliocentric radial velocity, the electron density Ne, the calculated extinction E_B−V = 0.68 · C(Hβ), and the extinction value near λ5007 Å, A5007 = 3.5 · E_B−V (Cardelli et al. 1989) are given in Table 1. The final reduced 1D spectra are shown in Figure 2. The obtained values of C(Hβ) in all spectra are high and correspond respectively to the high derived values of E_B−V. Assuming a Milky Way foreground extinction of E_B−V ≃ 0.77 in the direction of this galaxy (Richer et al. 2001), the internal extinction values A5007 vary in the range of 0.5 to 2.3. The latter implies that IC 10 contains a considerable amount of internal dust, a conclusion supported by many previous studies. Because candidate PN 7 was observed at high airmass (1.8) but not at the parallactic angle, it is possible that some flux may have been lost in the blue and/or red parts of the spectra. As Hα images were used to place objects on the slit, we most likely lost flux in the blue. Based on Filippenko (1982), we estimate that we might have lost ∼30% in the spectral region of Hβ and ∼50–60% in the spectral region of Hγ. For this reason, the extinction values found for PN 7 and shown in Table 1 should be considered upper limits. Our measured total [O iii] λλ5007 emission line fluxes for both observed candidates are about 20-30% lower than those presented by Magrini et al. (2003b). This is probably due to a combination of non-photometric conditions during our observations and the non-parallactic observation angle used for PN 7. Fortunately, the uncertain extinction determination for PN 7 does not affect the results presented in Section 4.

The derived radial velocities of PN 7a and PN 7b are close to each other, supporting the idea that both objects belong to the same complex. Their velocities are also close to the optical velocity of IC 10 Vhel = −348 km s−1 (Huchra et al. 1999). Shostak & Skillman (1989) found that H1 velocities in IC 10 range from −300 to −400 km s−1. Comparison of PN 9’s position and its optical radial velocity with the 2D H1 velocity distribution (Figure 7 from Shostak & Skillman 1989) shows agreement to within the uncertainties of our velocity measurements. Thus, our radial velocities for both PN 7 and PN 9 support the idea that the observed PN candidates indeed belong to IC 10.
Table 1. Line intensities of the observed PN candidates in IC 10

| $\lambda_0$(Å) Ion | PN7a | PN7b | PN9 |
|-------------------|------|------|-----|
|                   | $F(\lambda)/F(H\beta)$ | $I(\lambda)/I(H\beta)$ | $F(\lambda)/F(H\beta)$ | $I(\lambda)/I(H\beta)$ | $F(\lambda)/F(H\beta)$ | $I(\lambda)/I(H\beta)$ |
| 4340 H$\gamma$    | 0.25±0.05 | 0.46±0.116 | 0.24±0.05 | 0.37±0.08 | 0.32±0.11 | 0.49±0.15 |
| 4861 H$\beta$     | 1.00±0.08 | 1.00±0.124 | 1.00±0.10 | 1.00±0.12 | 1.00±0.18 | 1.00±0.19 |
| 4959 [O iii]      | 1.46±0.12 | 1.26±0.109 | 0.65±0.07 | 0.58±0.07 | 4.35±0.53 | 3.61±0.65 |
| 5007 [O iii]      | 4.84±0.37 | 3.98±0.327 | 2.11±0.19 | 1.83±0.18 | 14.81±1.77 | 11.85±1.93 |
| 5876 He i         | 0.36±0.04 | 0.12±0.016 | 0.26±0.05 | 0.15±0.03 | —        | —        |
| 6548 [N ii]       | 0.37±0.04 | 0.06±0.009 | 0.31±0.05 | 0.11±0.02 | 0.35±0.12 | 0.11±0.04 |
| 6563 H$\alpha$    | 14.67±1.11 | 2.76±0.404 | 8.46±0.75 | 2.91±0.30 | 9.73±1.18 | 2.91±0.44 |
| 6584 [N ii]       | 1.13±0.14 | 0.20±0.031 | 0.97±0.10 | 0.33±0.04 | 1.22±0.23 | 0.36±0.08 |
| 6678 He i         | 0.12±0.02 | 0.02±0.004 | —        | —        | —        | —        |
| 6717 [S ii]       | 0.80±0.07 | 0.13±0.016 | 0.71±0.08 | 0.23±0.03 | —        | —        |
| 6731 [S ii]       | 0.58±0.06 | 0.09±0.013 | 0.49±0.06 | 0.15±0.02 | —        | —        |
| 7136 [Ar iii]     | 0.66±0.06 | 0.08±0.010 | 0.32±0.04 | 0.08±0.01 | —        | —        |

C(H$\beta$) dex | $\leq$2.10±0.04$^a$ | $\leq$1.35±0.07$^a$ | 1.44±0.12 |
F(H$\beta$)$^b$ | 7.50 | 4.7 | 0.66 |
EW(abs) Å       | 4.00 | 4.30 | — |
EW(H$\beta$) Å  | 440±14 | 174±10 | 142±17 | — |
N$_e$(SiII)(cm$^{-3}$) | 40±60 | $\leq$10 | — |
Rad. vel. km s$^{-1}$ | $-361±25$ | $-355±34$ | $-391±43$ | — |
E$_{B-V}$ mag    | $\leq$1.43±0.03 | $\leq$0.92±0.05 | 0.98±0.08 |
A$_{S$00}$ mag   | $\leq$5.01±0.10 | $\leq$3.22±0.17 | 3.43±0.29 |

$^a$ Note: PN 7a and 7b were not observed at the parallactic angle. See Section 3 for more details.

$^b$ Observed flux in units of 10$^{-16}$ ergs s$^{-1}$ cm$^{-2}$.

4 DISCUSSION

4.1 PN or compact H$\Pi$ region?

Most extragalactic PN candidates are point-like sources. The task of distinguishing between PN and compact H$\Pi$ regions in dwarf irregular and spiral galaxies is extremely difficult and cannot be accomplished with morphological criteria alone. Usually, the line ratio R = I([O iii] 5007)/I([N ii] λ6583) is in use in searches for PN candidates with narrow-band imaging in H$\alpha$ and [O iii] λ5007 lines. A criterion of R > 1.6 for PN candidates was adopted by Ciardullo et al. (2002) after the analysis of a large sample of extragalactic PNe. However, it is well known that the ratio R is a function of the absolute magnitude of PNe, hence many extragalactic PN candidates can have R < 1.6. Magrini et al. (see, e.g., the list of PN candidates from 2003b, 2005a). Definitive classification/selection can only be performed with classification/diagnostic diagrams, after candidate spectra have been obtained. PNe spectra have the same emission lines as H$\Pi$ regions, but the central stars of PNe are hotter than the OB stars in H$\Pi$ regions, and the line intensity ratios are different for this reason. In addition, the electron densities in most PNe are higher than those in H$\Pi$ regions. Empirical emission line diagrams are often used both to distinguish between different classes of ionized nebulae in the Galaxy (Schweiker & D’Odorico 1976; Sabadini et al. 1977; Garcia-Lario et al. 1991; Riesgo-Tirado & Lopez 2002; Magrini et al. 2003a; Riesgo-Tirado & Lopez 2006) and different types of emission-line galaxies (ELGs, e.g., Heckman 1981; Baldwin et al. 1981; Veilleux & Osterbrock 1987; Ugrumov & 1999). Unfortunately, unlike ELG classification based on such diagrams, to our knowledge there are no published quantitative criteria for distinguishing PNe from H$\Pi$ regions. Analyses using the [O iii] 5007/H$\beta$ ratio for classification purposes are absent from the literature as well, even though [O iii] 5007 is the strongest line in most PN spectra.

To fill this gap and to derive quantitative criteria for the objective spectral classification of PN candidates, we first used a subsample of spectra of H$\Pi$ regions (H$\Pi$ galaxies) from the SDSS database (Knizev et al. 2004). Their line intensity ratios are shown in Figures 3 and 4. These data cover very large ranges for a variety of emission line intensity ratios in H$\Pi$ galaxies of different excitation types, and therefore can be used to define their loci properly. Secondly, we compiled from the literature a sample of extragalactic PNe with published spectra or emission line measurements. Data from the following galaxies were included: M 31 (Jacoby & Ford 1986; Jacoby & Ciardullo 1994; Knizev et al. 2005a, 2005b), M 33 (Magrini et al. 2003a), LMC and SMC (Aller 1983; Mon et al. 1988; Boroson & Liebert 1989; Meatheringham & Dopita 1991a; Vassiliadis et al. 1992; Jacoby & Kaler 1993; Dopita et al. 1993; Leisy & Dennefeld 2000), Sextans A and Sextans B (Knizev et al. 2005a, 2005b, Magrini et al. 2005a), Leo A (Knizev et al. 2005a), NGC 6822 (Richer & McCall 2007), Fornax (Knizev et al. 2006a, 2007), Sagittarius (Walsh 1997; Zijlstra et al. 2006), NGC 147 (Goncalves et al. 2007), M 32 (Jenner et al. 1971), NGC 205 (Richer & McCall 1995), and NGC 5128 (Walsh et al. 1999). In cases for which measurements of [Sii] lines in PNe and PN candidates were not available, and for which we have data (PNe in Sextans B and PN 7 in IC 10), 2σ upper limits were calculated. These upper limits are shown as well with arrows. Our data for IC 10 were not used for criteria selection.
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Figure 3. Classification diagrams for PNe/H\textsuperscript{II} galaxy separation. The SDSS DR1 strong emission-line H\textsuperscript{II}-galaxies from Kniazev et al. (2004) are plotted as dots. The data for extragalactic PNe are overplotted with different symbols: from M 31 as empty circles, from NGC 205 and M 32 as empty triangles, from Fornax, Sagittarius and NGC 147 as crossed squares, from NGC 5128 as crosses (x), from the SMC as pluses (+), from the LMC as filled diamonds, from Leo A and NGC 6822 as empty squares, from Sextans A as a star, from Sextans B as filled triangles, from M 33 as filled lozenges and the current data for IC 10 as filled squares. The positions of the observed IC 10 PN candidates are labeled in the upper panel. The points representing upper limits are shown with arrows in the lower panel. The solid line shows the models from Kewley et al. (2001) used for AGN/H\textsuperscript{II} galaxy separation.

In total, we collected a sample of 259 different extragalactic PNe with measurements of all the emission line intensities we are considering: [O\textsc{iii}] \(\lambda5007\), H\textbeta, H\alpha, [N\textsc{ii}] \(\lambda6584\), and [S\textsc{ii}] \(\lambda\lambda6716,6731\). We did not require separate measurements of the [S\textsc{ii}] \(\lambda\lambda6716,6731\) lines for this sample, which we used for calculation of the overall selection efficiency. A subsample of 227 extragalactic PNe with resolved measurements of [S\textsc{ii}] \(\lambda\lambda6716,6731\) was used to estimate the selection efficiency for criteria involving the use of the sulphur lines.

Our analysis has shown that it is possible to classify/separate almost all collected extragalactic PNe, if at least two (main) diagrams are used: log(([O\textsc{iii}] \(\lambda5007\)/H\textbeta)) vs. log([N\textsc{ii}] \(\lambda6584\)/H\alpha) and log([S\textsc{ii}] \(\lambda\lambda6716,6731\)/H\alpha) vs. log([N\textsc{ii}] \(\lambda6584\)/H\alpha). However, it is worth noting that most of these PNe can easily be separated with only the first diagram, which utilizes the strongest emission lines easily detectable in both PNe and H\textsuperscript{II} regions. It is clearly seen in the top panel of Figure 3 that most PNe are located in the same area as AGNs and can be easily distinguished with the model track of Kewley et al. (2001), often used for AGN/H\textsuperscript{II} segregation (see, e.g., Kniazev et al. 2004). The demarcation line from this model is shown as a solid line in Figure 3. We
use this to construct the first quantitative criterion for the PNe selection:

$$\log \left( \frac{[O \text{iii}]/H\beta}{[N \text{ii}]/H\alpha} \right) \geq 0.61 / \log \left( \frac{[N \text{ii}]/H\alpha}{0.47} \right) + 1.19$$  \hspace{1cm} (1)

This allows us to identify 76% of all objects from the compiled list as PNe. However, the subsample of PN in Leo A, four PNe in Sextans B, the PN 7a and PN 7b candidates in IC 10 and some PNe candidates from M33, LMC and SMC form a locus in the area of H II regions, so that other classification diagrams must be used to separate them. The use of the diagram $\log ([O \text{iii}] \lambda 5007/H\beta) \text{ vs. } \log ([S \text{ii}] \lambda 6716,6731/H\alpha)$ (bottom panel of Figure 3) and the Kniazev et al. (2001) model’s demarcation line $\log ([O \text{iii}]/H\beta) \geq (0.72 / \log ([S \text{ii}]/H\alpha) - 0.32) + 1.30$ does not help, since more PNe appear in the region of H II compared with those found in the diagram $\log ([O \text{iii}] \lambda 5007/H\beta) \text{ vs. } \log ([N \text{ii}] \lambda 6584/H\alpha)$. The classification efficiency of criterion (2) for our compiled PNe sample is only 62%. Thus we did not use the classification diagram $\log ([O \text{iii}] \lambda 5007/H\beta) \text{ vs. } \log ([S \text{ii}] \lambda 6716,6731/H\alpha)$ in any further analysis.

The separation of supernova remnants (SNRs) is outside the scope of the current study. However, we suggest that most SNRs can also be distinguished with the use of the diagram $\log ([O \text{iii}] \lambda 5007/H\beta) \text{ vs. } \log ([N \text{ii}] \lambda 6584/H\alpha)$, the model lines from Kewley et al. (2001), and the addition of model lines for LINER selection from Veilleux & Osterbrock (1987) and Baldwin et al. (1981), as was demonstrated in Kniazev et al. (2004). The latter is possible since both LINERS and SNRs have significant emission contributions from shock excitation. All such objects are located below the line corresponding to criterion (1). The locus of SNRs found in M 33 (Magrini et al. 2003a) supports this conclusion.

The diagram $\log ([S \text{ii}] \lambda 6716,6731/H\alpha) \text{ vs. } \log ([N \text{ii}] \lambda 6584/H\alpha)$ (shown in the top panel of Figure 3), can be used as an additional diagnostic for the identification of PNe. From the analysis of our compiled PN data we have found that, with the use of only the criterion:

$$\log ([S \text{ii}]/H\alpha) \leq 0.63 \cdot \log ([N \text{ii}]/H\alpha) - 0.55$$  \hspace{1cm} (3)

83% of our PNe can be recovered. However, with the combined use of criteria (3) and (1), 99% of PNe can be distinguished from H II regions (i.e., all but two cases). Any analysed object is classified as a PN if it is located in the PNe locus according to at least one of the cited criteria. It should be noted that, for many extragalactic PNe the detection of [S ii] $\lambda\lambda 6716,6731$ lines is difficult, since the ratio $I([S \text{ii}] \lambda 6716,6731)/I(H\beta)$ is typically $\sim 0.5$–5%. However, upper limits for this line ratio can be successfully used in this situation, similar to the cases of the PNe from Sextans B and the candidate PN 9 in IC 10. This second criterion is also very useful for rejecting possible SNRs, which fill the locus shown with the dashed line in the top panel of Figure 3.

The last classification diagram we considered is the relation between the flux ratio of the two lines of the [S ii] $\lambda\lambda 6716,6731$ doublet and that of the flux ratio of the [N ii] $\lambda 6584$ and Hα lines: $[S \text{ii}] \lambda\lambda 6716,6731$ vs. $\log ([N \text{ii}] \lambda 6584/H\alpha)$. This is shown in the bottom panel of Figure 3. The criteria below

$$[S \text{ii}] \lambda\lambda 6716,6731 \leq -0.135 \cdot \log ([N \text{ii}]/H\alpha) + 0.90$$  \hspace{1cm} (4)

32% + 1 \cdot [S \text{ii}] / [O \text{ii}]$.

4.2 On the brightest PN in IC 10 and its distance

The IC 10 candidate PN 9 observed in this work can be confidently classified as a true PN according to both criteria (1) and (2). However, according to all classification diagrams shown in Figures 3 and 4, IC 10 candidates PN 7a and PN 7b, cannot be selected as PNe and for this reason were finally classified as compact H II regions. An additional reason to believe that PN 7a and PN 7b are H II regions is the detection of continuum in their spectra (see Figure 2).

The absolute magnitude cutoff of the PN $[O \text{iii}] \lambda 5007$ luminosity function (PNLF) is considered to be constant in large galaxies with a large population of PNe, and is equal to $M_{5007}^\text{PN} = -5.47$ (Ciardullo et al. 2002). For dwarf galaxies, this cutoff is likely shifted towards the fainter magnitudes as a function of the galaxy mass and the population size (Méndez et al. 1993). Dopita et al. (1992) also examined the effects of metallicity on the luminosity of the brightest PN. According to their models, the variation of the cutoff magnitude $M_{5007}^\text{PN}$ with oxygen abundance is described by the relation

$$\Delta M_{5007} = 0.928 \cdot [O/\text{H}]^2 + 0.225 \cdot [O/\text{H}] + 0.014,$$  \hspace{1cm} (6)

where $[O/\text{H}]$ is the system’s logarithmic oxygen abundance referenced to the solar value $12 + \log(O/H) = 8.87$ (Anders & Grevesse 1989). Ciardullo et al. 2002 studied...
the accuracy of $M_{5007}$ and found that $M_{5007} = -14.47 \pm 0.05$ after the correction for metallicity using equation (3).

The brightest PNe absolute magnitudes should be reasonably close to $M_{5007}$. With PN 7, the brightest candidate in IC 10 from [Magrini et al. (2003a)], $M_{5007}$ for this galaxy can be calculated as $-3.34$, where for candidate PN 7 $m_{5007} = 21.71$ [Magrini et al. (2003a)], $A_{5007} = 2.70$, assuming background extinction of $E_{B-V} = 0.77$ [Richer et al. 2001; Hunter 2001] and a distance modulus $(m-M) = 24.35$ [Demers et al. 2004]. Adopting the value of $12 + \log(O/H) = 8.19$, $[O/H] = -0.68$ and $\Delta A_{IC10} = 0.29$, respectively for IC 10 we expect the 'corrected' cutoff magnitude for the IC 10 PNLF to be $M_{5007} = -4.18$. Thus, the calculated $M_{5007}$ for PN 7 appears $\sim 1^m 15$ brighter than the standard value.

After the rejection of the PN 7 candidate as an H II region based on the results of our observations, the PNLF for PN candidates in IC 10 is shown in Figure 5 where data from [Magrini et al. (2003a)] have been binned into $0^\circ 6$ intervals. Poisson $\pm \sigma$ error bars are shown for the detected number of PNe in these bins. We fitted this PNLF with a "universal" PNLF [Ciardullo et al. 1989], taking only the brightest PNe (first three bins, eleven PNe in total) into account and using a uniform foreground extinction of $E_{B-V} = 0.77$ [Richer et al. 2001; Hunter 2001]. The result of this fitting and Poisson errors are also shown in Figure 5. With this small sample we obtained the distance modulus $(m-M) = 24.30 \pm 0.18$ (including the error in $M_{5007}$), corresponding to a distance $D = 725^{+63}_{-33} \text{kpc}$; this is very close to the value from [Demers et al. 2004]. This distance modulus is also consistent with the recent estimate $(m-M) = 24.48 \pm 0.18$ in [Vaccarella et al. 2007], obtained from the study of individual RGB stars. With the PN data in hand, a distance to IC 10 of 950 Mpc [Massey & Armandroff 1992; Hunter 2001] seems implausible. The PNLF dip after the first three bins is likely a result of incompleteness, or could arise in a young population in which central star evolution proceeds very quickly [Jacoby & De Marco 2003]. Such a dip is also detected in the PNLFs in NGC 6822 [Leisy et al. 2005], the Small Magellanic Cloud and M 33 [Jacoby & De Marco 2002; Ciardullo et al. 2004].

Of course, PN candidates, not confirmed PNe, were used for the PNLF calculation (except in the case of PN 9, which was confirmed in this paper), making this result for the IC 10 PNLF distance somewhat preliminary. However, all the bright PN candidates that were used for the PNLF fitting have $R > 1.6$ [Magrini et al. 2003a] and thus have a very high probability of being real PNe.

The calculated distance to IC 10 obviously depends on the extinction values used; higher extinction values would place IC 10 even closer to us. The total extinction value toward IC 10 is a combination of foreground (i.e., Galactic) extinction, and the extinction internal to IC 10; this latter quantity is quite uncertain, and for this reason only foreground extinction is usually considered (as we have done in this work). The great advantage of PNLF distance calculations (compared to other methods) is that, in principle, the total extinction along the line of sight can be calculated after proper spectral observations of PN candidates and calculations of C(H\beta) for each PN [Jacoby, Walker, & Ciardullo 1990]. For this reason further spectroscopic observations of other PN candidates in IC 10 are very important. On the other hand, total extinctions calculated using C(H\beta) for PNe have to be used carefully, since could be strongly affected by extinction in localised circumstellar material. For this reason we do not make further use of the extinction we derive from the spectrum of PN 9 in IC 10; instead, we plan to map the line-of-sight extinction in its neighbourhood through observations of nearby H II regions.

5 CONCLUSIONS

In this paper we present the first results of follow-up spectroscopy of PN candidates in the Local Group starburst galaxy IC 10. Based on our data and the discussion above, we draw the following conclusions:

1. From the obtained spectral data and the emission line diagnostic diagrams we have found that the brightest candidate PN 7 from the list of [Magrini et al. (2003a)] is not a genuine PN, but rather a close pair of compact H II regions. The calculated absolute magnitude $M_{5007}$ for PN 7 is about $1^m 15$ brighter than the standard maximum value from the PN luminosity function expected at the approximate distance of IC 10.

2. We have found that PN 9, obtained from the same list of candidate PNe, is a true PN, and thus is the first confirmed PN in IC 10.

3. With the available PN candidate data, we estimate the PNLF distance to IC 10 as $725^{+63}_{-33} \text{kpc}$, a distance modulus of $(m-M) = 24.30^{+0.18}_{-0.10}$.

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Spectroscopy of two PN candidates in IC 10
