The Local Group Census: searching for PNe in IC 1613, WLM and GR8

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ABSTRACT
In the framework of the Local Group Census (LGC), a survey of the Local Group (LG) galaxies above Dec=−30°, which is aimed at surveying their populations with strong emission lines, we have searched for planetary nebulae (PNe) in the low-metallicity dwarf irregular galaxies IC 1613, WLM, GR 8. Two new candidate PNe have been found in IC 1613, one in WLM and none in GR 8. The observations presented in this paper, together with the previous results from the LGC, represent the first step in the study of the PN population in low-metallicity, dwarf irregular galaxies of the Local Group. They will be followed by deep spectroscopy to confirm their nature and to study their physical-chemical properties. We used the observed number of PNe in each LG galaxy to estimate a lower limit to the mass of the intermediate-age population which was compared to the Star Formation Rate (SFR) of LG dwarf galaxies. These results are in agreement with those from accurate star formation history (SFH) analysis for these small galaxy systems.

Key words: planetary nebulae: individual: IC 1613, WLM– Galaxies: individual: IC 1613, WLM, GR 8

1 INTRODUCTION
The Local Group consists of three spiral galaxies and a large number of dwarf galaxies (~90% of its 40 known members). This proportion of galaxy types may be typical of the local Universe as similar distributions are known to exist in nearby groups (Miller 1996) and clusters (Phillips et al. 1998). The dwarf galaxies (irregular, spheroidal or elliptical) of the LG are of particular interest as their proximity allows us to study them in detail, testing predictions concerning their formation and evolution, as, for instance, the evolution of different kind of dwarfs (Richer & McCall 1995) or their star formation histories (Aparicio 2001).

Furthermore, their study is relevant because, according to the hierarchical scenario of galaxy formation, dwarf galaxies are the first structures to form and from their merging larger galaxies are built (Nagashima & Yoshii 2004). Moreover, low-luminosity dwarf galaxies, as those discussed in this paper, are metal poor and are expected to have abundances close to primordial values (Kunth & Ostlin 2000). Thus the abundances derived there can be useful in extrapolating primordial He/H (Peimbert & Torres-Peimbert 1974; Lequeux et al. 1979).

It is also interesting to compare the overall star formation history (SFH) of the Universe predicted by Madau, Pozzetti & Dickinson (1998) with the SFHs of galaxies of different morphological type that exist in the LG (Mateo 1998; Aparicio 2001). This is fundamental in order to understand the variation of SFH from the global average in galaxies of differing morphological type (Renzini 1995; McGaugh & Bothun 1994).

A quantitative SFH can be obtained with the
colour-magnitude diagram (CMD) technique (cf. Aparicio & Gallart [2004]). This technique involves three main ingredients: i) the data, from which a deep observational CMD can be plotted; ii) stellar evolution and a bolometric correction libraries providing colors and magnitudes of stars as a function of age, mass, and metallicity; and iii) a method to relate the number of stars populating different regions of the observational CMD with the density distribution of stars as a function of age, mass, and metallicity, as predicted by stellar evolution theory (see Aparicio & Gallart 2004 for a complete review). This method can, in principle, constrain the entire star formation and chemical history of a galaxy, but, of course, it depends on the precision of the input models and on the assumptions (Aparicio & Gallart 2004). Moreover, since the overall results of this method are model dependent, complementary specific evolutionary phases can be used as age-tracers to mark different populations and to infer the presence of a given age component (Mateo 1998).

In this paper, we present new results from the latest study of individual group members as part of the continuing LG census. This census is a narrow- and broad-band imaging survey of the galaxies of the LG, visible from the Isaac Newton Group of telescopes (ING), whose aim is to provide an excellent opportunity to observe stellar populations in a low metallicity environment. In fact, its oxygen abundance as derived from H ii regions is approximately \(12 + \log (O/H) = 7.7\) (Skillman, Kennicutt & Hodge 1989; in a part of the Local Group relatively free of galaxies, at a distance of 925 kpc (vdB00). Dolphin (2000) studied with the Hubble Space Telescope the SFH in a portion of WLM. It appears to have begun no more than 12 Gyr ago, forming more than half of its stellar population by 9 Gyr ago. The SFR has subsequently gradually decreased until a recent increase in activity starting between 1 and 2.5 Gyr ago, but is still continuing to the present time. Recent star formation is indicated by several H ii regions around O-type stars, as observed by Hodge & Miller (1995).

To date no candidate PN is known in this galaxy. In fact, Minniti & Zijlstra (1997) found the two candidate PNe proposed by Jacoby & Lesse (1981) to be ordinary stars. The other candidate PN identified by Minniti & Zijlstra (1996;1997) was found to be a compact H ii region (Zijlstra, private communication).

GR 8 was first discovered by Reaves (1956) and it was catalogued as DDO 155 by van den Bergh (1953). It is a suspected member of the Local Group (vdB00), but observations of a single Cepheid by Tolstoy et al. (2003) found an enhanced star formation rate (SFR) from 13 to 6 Gyr ago. A survey for emission-line objects was done in this galaxy by Lequeux, Meyssonier & Azzopardi (1987) who found one candidate PN.

The Wolf-Lundmark-Melotte (WLM) galaxy was discovered by Woll (1923) and independently by Lundmark (1923) and by Melotte (1924). WLM (called also DDO 221. van den Bergh (1964) is a Local Group metal-poor dwarf irregular \(12 + \log (O/H) = 7.7\); Skillman, Kennicutt & Hodge (1989), in a part of the Local Group relatively free of galaxies, at a distance of 925 kpc (vdB00). Dolphin (2000) studied with the Hubble Space Telescope the SFH in a portion of WLM. It appears to have begun no more than 12 Gyr ago, forming more than half of its stellar population by 9 Gyr ago. The SFR has subsequently gradually decreased until a recent increase in activity starting between 1 and 2.5 Gyr ago, but is still continuing to the present time. Recent star formation is indicated by several H ii regions around O-type stars, as observed by Hodge & Miller (1995).

The gas-rich dwarf irregular galaxy IC 1613 was first discovered by Woll (1923), and because of its proximity (730 kpc, Dolphin et al. 2001), its high Galactic latitude (-60$^\circ$.6) and consequently small Galactic extinction, has provided an excellent opportunity to observe stellar populations in a low metallicity environment. In fact, its oxygen abundance as derived from H ii regions is approximately \(12 + \log (O/H) = 7.7\) (Skillman, Kennicutt & Hodge [1989]; Lee, Grebel & Hodge [2003]). Moreover, IC 1613 is a relatively isolated non-interacting irregular galaxy, as proven by the lack of stellar clusters generated by interactions with other galaxies (van den Bergh 2000). From an evolutionary point of view, it is a very primitive galaxy because the stellar mass is comparable to the gas mass (Hodge et al. 1991).

1 See http://www.ing.iac.es/~roncorradi/LGC for the description of the project.
night of September 2004, which was photometric, was used to calibrate the observations of October 2002. Each exposure was split into multiple sub-exposures. The total exposure times, the number of exposures, and the seeing in each filter are listed in Table 2.

Several observations of the spectrophotometric standard stars BD+33 2642 and G191-B2B (Okel1994) were made each night during the February 2001 run, while Feige 110 (Okel1994) was observed during the September 2004 run.

We complemented our observations with images of WLM from the ESO archive, taken with VLT+FORS1 on October 2002, and with observations of IC 1613 we obtained on September 2004 with VLT+FORS2 (see Table 2).

The filters used for the FORS1 observations were [O III] (500.5/0.8 nm) and [O III]/6000 (510.9/0.8 nm), while for FORS2 observations H α (656.3/6.1 nm) and R (655.0/165.0 nm) were employed. [O III]/6000 and R filter images were used for continuum subtraction of the [O III] and Hα images, respectively.

The VLT data taken with the [O III] filter were calibrated using the INT observations. Scaling the diameters of INT and VLT telescopes with the exposure time, the INT images should be as deep as the VLT images. Because of the better seeing, the VLT images through the [O III] filter are however about 1 mag deeper than the corresponding [O III] INT images.

### Table 1. Data on the observed galaxies.

| Name   | R.A. (2000.0) Dec. | Type | Distance (kpc) | Optical size | M_V | 12+log(O/H) † | M (M☉) |
|--------|-------------------|------|----------------|--------------|-----|---------------|--------|
| IC 1613 | 01 h 04 m 47.8 +02° 07' 04" | Ir V (1) | 725 (1) | 10’x20’ | -15.3 (1) | 7.7 (7) | 1x10^8 (10) |
| WLM    | 00 h 01 m 58.1 -15° 27' 39" | IrIV-V (1) | 925 (1) | 6.5’x12.6’ | -14.4 (1) | 7.7 (8) | 1.5x10^8 (2) |
| GR 8   | 12 h 58 m 07.4 +14° 13' 03" | dIrr (2) | 2200 (3) | 1.1’x1.0’ | -11.6 (2) | 7.4 (9) | 7.6x10^6 (1) |

References: R.A. and Dec. come from NED. (1) van den Bergh (2000A); (2) Mateo (1998); (3) Tolstoy et al. (1995); (4) Ables (1971); (5) Gallouet et al. (1973); (6) NED; (7) average of values obtained by Skillman, Kennicutt & Hodge (1989) and Lee, Grebel & Hodge (1993); (8) Skillman, Kennicutt & Hodge (1989); (9) Skillman et al. (1988); (10) Lake & Skillman (1988). † Oxygen abundances reported in the Table have been computed from spectra of H II regions.

### Table 2. Summary of the observations: target galaxies, date of observations, telescope and instrument, total exposure times, number of exposures, seeing, and filters.

| Target | Date | Inst. | Exp. (sec) | N. Seeing ("') | Filter |
|--------|------|-------|------------|----------------|--------|
| G8     | Feb. 2001 | WFC@INT | 4800 | 1.0 | Hα+[N II] |
|        |       |       | 3600 | 1.0 | [O II] |
|        |       |       | 1800 | 1.0 | Str. y |
|        |       |       | 2400 | 1.0 | r' |
|        |       |       | 2400 | 1.0 | g' |
| IC1613 | Oct. 2002 | WFC@INT | 3600 | 1.3 | Hα+[N II] |
|        |       |       | 4800 | 1.3 | [O II] |
|        |       |       | 1800 | 1.3 | Str. y |
|        |       |       | 1200 | 1.3 | r' |
|        |       |       | 1200 | 1.7 | g' |
|        | Sept. 2004 |       | 300 | 1.1 | Hα+[N II] |
|        |       |       | 300 | 1.2 | [O III] |
| IC1613 | Sept. 2004 | FORS2@VLT | 200 | 2 | Hα |
|        |       |       | 20 | 2.0 | R |
| WLM    | Oct. 2002 | WFC@INT | 5600 | 1.3 | Hα+[N II] |
|        |       |       | 3200 | 1.6 | [O II] |
|        |       |       | 1600 | 1.6 | Str. y |
|        |       |       | 4000 | 1.2 | r' |
|        |       |       | 1800 | 1.6 | g' |
| WLM    | Oct. 2002 | FORS@VLT | 300 | 0.8 | [O II] |
|        |       |       | 300 | 0.8 | [O III]/6000 |

The filters used for FORS2 images were [O III] (500.5/0.8 nm) and [O III]/6000 (510.9/0.8 nm), while for FORS2 observations Hα (656.3/6.1 nm) and R (655.0/165.0 nm) were employed. [O III]/6000 and R filter images were used for continuum subtraction of the [O III] and Hα images, respectively.

The VLT data taken with the [O III] filter were calibrated using the INT observations. Scaling the diameters of INT and VLT telescopes with the exposure time, the INT images should be as deep as the VLT images. Because of the better seeing, the VLT images through the [O III] filter are however about 1 mag deeper than the corresponding [O III] INT images.

### 3 DATA REDUCTION AND ANALYSIS

The data reduction was done using IRAF3. First the data were processed by the ING WFC data-reduction pipeline [Irwin & Lewis 2001]: they were de-biased, flat-fielded, and linearity-corrected. Then they were corrected for geometrical distortion and subsequently all frames were aligned to a common reference frame. Finally the sky background was subtracted.

In order to search for emission-line objects, in GR 8 we subtracted from the [O III] frames the properly scaled Strömgren y frames, whereas for IC 1613 and WLM we used the g' frames as a continuum. For each galaxy we have chosen the best quality continuum, Strömgren y or g', to do the off-band subtraction.

For the VLT images of WLM, the scaled [O III]/6000 images were subtracted from the [O III] images. For the Hα+[N II] images of all galaxies, we used the correctly scaled r' frames as a continuum. Finally for the Hα images of IC 1613 taken with VLT, R was used as a continuum. The

3 IRAF is distributed by the National Optical Astronomy Observatories, which is operated by the Association of Universities for Research in Astronomy, Inc. (AURA) under cooperative agreement with the National Science Foundation.

http://archive.eso.org
search for unresolved emission-line objects in the continuum subtracted images was done visually at least three times per galaxy by different members of the team. In addition, we performed photometry of the unresolved sources in all the INT images with DAOPHOT (Stetson 1997) to build Hα+[N II] - r′ vs [O III] - g′ diagrams, obtaining in IC 1613 the same results as the visual search, while the PN of WLM was not recovered because of its proximity to a star (see Fig. 2).

The astrometric solutions were computed using the IRAF tasks CMAP and CCTRAN and the APM POSS1 + and USNO A2.0 (Monet et al. 1998) catalogues. The final accuracy was ~0.3 r.m.s.

## 4 CANDIDATE PLANETARY NEBULAE

We searched for PNe in our continuum-subtracted frames selecting objects which satisfy the following criteria (Magrini et al. 2000): i) they must appear in both the [O III] and Hα+[N II] images, but not in the continuum frames; and ii) they must be unresolved at the distance of IC 1613, WLM, and GR 8, on account of the typical physical size of PNe (0.1-1 pc). We found two objects in IC 1613 fulfilling these criteria, one in WLM and none in GR 8. Using both [O III] and Hα+[N II] images, the possibility that these PNe are background emission line galaxies (Méndez et al. 1993) can be excluded.

### 4.1 The completeness limit

The incompleteness in searching for emission-line objects results from a combination of the probability of missing an object in the emission-line image and of the probability of wrongly identifying a star in the continuum frame. To estimate the completeness limit of our search for PNe, i.e. the magnitude corresponding to a probability of non-identification of an emission-line object larger than 50% (defining the incompleteness according to Minniti & Zijlstra 1997), we added ‘artificial stars’ with various magnitudes within the range of luminosities expected for PNe (Jacoby 1989), in both [O III] and continuum images. We have then computed the recovery rate of such artificial objects (Magrini et al. 2002, M03). We found that in the three galaxies the recovery rate is about 50% for objects with 25.5≤m_{[O III]}≤26.5 in GR 8, and 24.0≤m_{[O III]}≤25.0 in IC 1613 and WLM using the INT images, while in the VLT images for objects with 25.0≤m_{[O III]}≤26.0. The recovery rate is 100% for brighter objects. The difference in the incompleteness magnitude listed above comes mainly from the difference in seeing of the data used. We noted that the three candidate PNe are placed at the edges of each system and not in their more populated regions. This might be due to the identification technique, which is less effective in very crowded regions.

### 4.2 The expected number of PNe

The number of PNe, as well as the number of stars in any post-main-sequence phase, is proportional to the luminosity of the host galaxy, as derived from a simple (i.e. coeval and chemically homogeneous) stellar population model (Renzini & Buzzoni 1986). Thus, a small number of PNe is expected in low-luminosity galaxies, such as the ones surveyed (see also Fig. 2 of M03). This trend is also expected when the galaxies have, in addition, a low-metallicity; since a full in the observed number of PNe has been suggested when [Fe/H]<-1.0 (see Fig. 3, M03).

As described above, IC 1613, WLM, and GR 8 are low-luminosity and low-metallicity galaxies, so their expected PN number is very small. From the V-band luminosity vs. number of PNe diagram (Fig. 2 of M03), and assuming a search as deep as that made for Sex B, i.e. complete up to mag_{OIII}=24.5 (M03), we infer that the expected observable number of PN for IC 1613 is ~10 and ~3 for WLM; while none is expected in GR8.

### 4.3 GR 8 and WLM

The result in GR 8 was expected from the low-luminosity of this galaxy and is in agreement with the survey of Jacoby & Lesser (1981) which did not find any PN. The result for WLM also statistically agrees with the small expected PN population size and the large distance to this galaxy. The PN found in WLM is barely detectable in LGC images, whereas it is very clear in the VLT FORS1 images (see Fig. 2). Its position and fluxes are reported in Table 3. It is marked in Figure 4. In Fig. 2 thumbnail images taken in the various filters of the PN are shown. It can be seen in the VLT [O III] images that the PN is projected very close to a star, which is the object near to the location of the PN in the continuum image and disappears in the continuum-subtracted images. In addition, we found that the two objects previously claimed to be candidate PNe (Jacoby & Lesser 1981) are instead stars because of their strong continuum emission in all broad band images, as already recognized by Minniti & Zijlstra (1997).

### 4.4 IC 1613

The objects belonging to IC 1613 presented in this paper are the first candidate PNe discovered in this galaxy. Lequeux, Meyssonier & Azzopardi (1987) in an objective-prism survey for emission-line objects in this galaxy identified one candidate PN, but neither a following survey for H II regions (Skillman, Kennicutt & Hodge 1989) nor this work could confirm this object. The two candidates lie inside the optical size of the galaxy (16′′×20′′), according to Ables (1971). The position and fluxes of the PN candidates are listed in Table 3 and marked in Figure 3. In Fig. 2 thumbnail images of these PNe taken in the various filters are shown.

A criterion which is generally considered when selecting extragalactic PN candidates is the ratio between the [O III] and the Hα+ [N II] fluxes, which allows a statistical discrimination with unresolved H II regions. The criterion adopted by Ciardullo et al. (2002) is R=I([O III])/I(Hα+ [N II])> 1.6 for PNe. The reason is that central stars of PNe are generally hotter than the OB stars that excite H II regions, and...
Searching for PNe in IC 1613, WLM and GR8

this produces in PNe an [O iii] flux higher than the Hα + [N ii] flux. The value 1.6 is an empirical value derived with a large sample of extragalactic PNe. The ratio R is a function of the absolute magnitude of the PN, as we can see in Fig. 1 reproduced from the paper by Ciardullo et al. (2002).

For low luminosity PNe, R ranges from 1.5-2 down to very low values of 0.1 or less. As the object designated as PN2 in IC 1613 has an extremely low absolute magnitude we can accept it as a PN candidate even with its low R ratio of ∼0.2, as can be seen from Fig. 1. In addition, both PN 1 and PN 2 are far from the main star formation regions, and this reduces the possibility of contamination with compact H II regions (Ciardullo et al. 2002). Furthermore the value of R might be effected by the extinction on the observed line ratios. The extinction can arise within the Galaxy, along the line of sight to the LG galaxy and intrinsic to the galaxy itself. Any extinction would depress [O iii] relative to Hα and consequently decrease the value of R. For all the galaxies considered in this paper, the Galactic latitudes are very high, but localised extinction may still occur. Regarding the galaxies themselves, none are gas/dust rich and their internal extinction is very low.

In spite of the 10 PNe expected, we detected only two candidate PNe in this galaxy, which may be a significant difference. Anyhow we can never be complete for objects such as PNe - for instance in our Galaxy we now know more than 2500 PNe, but 10 000-30 000 are expected (Zijlstra & Pottasch 1991). With reference to Fig. 2 by M03, the relatively large number of PNe found in Sextans B is an exception in the context of LG low-luminosity galaxies. In fact, we found that Sextans A, WLM, IC 1613 and IC 10 have PNe populations rather smaller than expected. M03 discussed the particular case of the starburst galaxy IC 10 whose central area is covered by large H II regions thus producing a loss in observable PNe because of the superposition of the large H II regions. For low-metallicity galaxies (like Sextans A, WLM, and IC 1613), M03 suggested that the small number of observed candidate PNe might be explained by the low metal content of the host galaxies, which would imply a reduced PN formation. Any firm conclusion in this sense is prevented by the small number statistics; deeper surveys would be needed to improve this situation.

4.5 The absolute magnitude of the PNe

Another aspect to be noted is the relative faintness of the discovered PNe. The absolute magnitude of the cutoff of the PNe [O iii] luminosity function (PNLF) in a galaxy with a large population of PNe is considered constant in large galaxies, with a value M⋆ = −4.47 (Ciardullo et al. 2002). For dwarf galaxies, the cut-off magnitude decreases to fainter limits as a function of the galaxy mass and population size (Méndez et al. 1993). In fact, the brightest candidate PNe of IC 1613 and WLM are much fainter than M⋆. Considering the distance modulus of 24.3 and E(B-V)~0.03 for IC 1613 (vdB00), we obtain an absolute magnitude for its brightest PN of 0.1 mag. For WLM, where the distance modulus is 23.8 and E(B-V)~0.02 (vdB00), we found the absolute magnitude of the brightest PN to be approximately −0.5. As said above, this is likely due to the small population size of PNe in these dwarf galaxies, for which the magnitude of the cutoff, M⋆, is shifted towards fainter magnitudes (Méndez et al. 1993).
Table 3. PN candidates in IC 1613 and WLM. Positions are at J2000.0. Observed \([\text{O} \text{ iii}]500.7\) and \(\text{H} \alpha\) fluxes are given in \(10^{-16}\) erg cm\(^{-2}\) s\(^{-1}\).

| Identification  | R.A. (2000.0) | Dec.    | \(F_{\text{[O III]}}\) | \(F_{\text{H} \alpha+\text{[N II]}}\) | \(m_{\text{[O III]}}\) |
|-----------------|---------------|---------|-------------------------|---------------------------------|-------------------|
| WLM PN1         | 0 02 03.33    | -15 29 30.4 | 5.6                     | 3.3                             | 24.4              |
| IC 1613 PN1     | 1 04 32.28    | +02 08 43.5 | 5.2                     | 2.3                             | 24.5              |
| IC 1613 PN2     | 1 04 43.72    | +02 03 40.7 | 1.5                     | 6.7                             | 25.8              |

Figure 2. [\text{O} \text{ iii}]-continuum, [\text{O} \text{ iii}], continuum, and \(\text{H} \alpha\)-continuum images of the discovered PNe are shown. The size of each image is approximately 0.7\(\prime\)\(\times\)0.7\(\prime\). For WLM PN1: the [\text{O} \text{ iii}] and [\text{O} \text{ iii}]/6000 (continuum) images are from VLT, and \(\text{H} \alpha\)-r\(\prime\) from INT. For IC 1613 PN1 and PN2: [\text{O} \text{ iii}] and g\(\prime\) (continuum) images are from INT, and \(\text{H} \alpha\)-R from VLT. North is at the top, East to the left.

5 INTERMEDIATE-AGE STAR FORMATION HISTORY

Given the mass range covered by PN progenitors, assumed to be classically between 0.8\(M_\odot\) (or a bit higher, 1 \(M_\odot\), cf. Phillips [2001]) and 8\(M_\odot\), the stellar population from which PNe derive is formed at intermediate ages (roughly 1 to 8 Gyr ago) during the history of a galaxy. One can evaluate the total mass of such a stellar population using the theoretical relation between the total luminosity of the population of PNe progenitors and the PNe number, obtained under the hypothesis of coeval, chemically homogeneous stars (Renzini & Buzzoni [1986]). The total luminosity of the population of PNe progenitors, \(L_{T_{\text{PNe}}}\), is related to the number of PNe, \(n_{\text{PNe}}\), to their lifetime, \(t_{\text{PNe}}\), and to the so-called evolutionary flux, \(\xi_{\text{PNe}}\). The number of stars with initial mass \(0.8M_\odot < M < 8M_\odot\) per unit luminosity leaving the Main Sequence each year is then given by the expression

\[
L_{T_{\text{PNe}}} = \frac{n_{\text{PNe}}}{t_{\text{PNe}}\xi_{\text{PNe}}}. \tag{1}
\]

Thus, counting planetary nebulae and estimating the mean mass of the PNe progenitors we have a measure of the total mass of the intermediate-age stellar population, or at least a lower limit to it, when the PNe survey is not complete. Using a lifetime of \(\sim 10,000\) yrs for the PN phase, a mean specific evolutionary flux of \(2\times10^{-11}\) \(yr^{-1}\) \(L_\odot^{-1}\) (Renzini & Buzzoni [1986], Méndez et al. [1993], Buzzoni & Arnaboldi [2004]), a mean progenitor mass of \(\sim 1.5 M_\odot\) (computed using the Initial Mass Function by Scalo [1998], corresponding to a luminosity of \(\sim 5L_\odot\)), the lower limit to the intermediate-age stellar mass in the LG galaxies can be estimated. The intermediate-age stellar mass is proportional to the number of PNe, and with the approximations described above, we found that about \(2\times10^6 M_\odot\) were formed for each PN observed.

We used all the candidate PNe discovered in the Local Group by several authors (see references below) with
Figure 4. VLT [O iii] image of the galaxy WLM. North is at the top, East to the left. The size is approximately 7′×12′. The candidate PN is marked with a cross.

the on-band/off-band or similar techniques, and the criteria described in Sect. 4, considered as bona fide PNe for the following reasons. The first is that these criteria give a good confidence on the PN nature of the candidate. For instance, a follow-up spectroscopic study of PN candidates detected in M 33 by Magrini et al. (2000) confirmed more than 70% as PNe (Magrini et al. 2003A), even if the criterion of R > 1.6 was not used. Among the remaining 30% objects, some indetermination remains between low-excitation PNe and compact H II regions, which have similar spectroscopic and photometric features. The second reason is that it is impossible to study the statistical properties of PN population in the LG if considering only spectroscopically confirmed PNe since spectroscopic observations have been obtained for only ~10% of the total number of LG PNe. In addition, once obtained, spectroscopy cannot provide complete confidence in the determination of the nature of the objects, in many cases because of the faintness of the objects (Jacoby 2005).

In Figure 5 we show the result, plotting the total stellar mass of the galaxies (values from vdB00) vs. the observed number of PNe (left vertical axis). The latter is proportional to the mass of the intermediate-age stellar population (right vertical axis) with a constant of proportionality of 2×10^6. Errors amount to ~30% in the estimate of the total stellar mass of galaxies, and to ~50% in the estimate of the intermediate-age mass for the galaxies where we obtained the number of PNe within 4 mag from the cutoff of the PNLF (upper panel). For the galaxies where we have only the number of observed PNe (lower panel), only a lower limit to the intermediate-age mass can be given. The references on the number of PNe in the Local Group and also on their spectroscopic confirmation, if any, are: M 31 2764 PNe identified with the Planetary Nebulae Spectrograph by Merrett et al. (2003); ~30 confirmed with spectroscopy by Jacoby & Ciardullo (1994), Stasinska et al. (1998); MW ~2400 (1143 + 242 true and probable PNe in Acker et al. 1992, and ~1000 in Parker et al. 2003); M 33 152 PNe identified by Ciardullo et al. (2004); (30 confirmed by Magrini et al. 2003A); LMC ~1000 estimated, 350 discovered by Jacoby (2005) and 700 newly discovered by Reid & Parker (2003) (200 confirmed by Leisy & Dennefeld 2005B); SMC 132 estimated and 101 discovered Jacoby (2005) (~70 confirmed by Leisy & Dennefeld 2005B); M 32 30 (Ciardullo et al. 1988) (14 confirmed by Richer & McCall 2002); NGC 205 35 Corradi et al. (2003) (13 confirmed by Richer & McCall 2002); IC 10 16 Magrini et al. (2003B); NGC 6822 17 Leisy et al. (2003) (6 confirmed, Leisy, private communication); NGC 185 5 Corradi et al. (2003) (5 confirmed by Richer & McCall 2002); NGC 147 9 Corradi et al. (2003); Sagittarius 3 Zijlstra (2002) (confirmed); Forbush 1 Danziger et al. (1978) (confirmed); Pegasus 1 Jacoby & Lesser (1981); Leo A 1 Magrini et al. (2003B) (confirmed, Leisy, private communication); NGC 3109 18 Prada et al. (2003); Sextans B 5 Magrini et al. (2002) (confirmed by Magrini et al. 2003); Sextans A 1 Magrini et al. (2003B) (confirmed by Magrini et al. 2003).

Despite the large errors, a linear trend can be traced (the continuous line in the upper panel of Figure 5), where the total stellar mass of the galaxies is plotted versus the number of PNe, for all cases in which we could estimate their population size corrected to a completeness limit of 4 magnitudes below the PNLF cutoff. This number is extrapolated from the empirical formula of the luminosity function Jacoby (1988) for the LG galaxies where the completeness limit in the search for PNe was known, and where PNe above this limit were discovered. From this plot we can infer which galaxies had relatively strong star formation during the past ~1–8 Gyrs, i.e. in the period corresponding to the formation of the PNe progenitors. In particular, we can compare the location of dwarf galaxies in Figure 5 with their SFHs reviewed by Mateo (1998). We find that the galaxies which show little star formation during the past 1–8 Gyrs, i.e. the galaxies with a relative star-formation rate <0.2 during that period of time (cf. Figure 8 of Mateo 1998), generally lie in the diagram below the continuous line (filled squares). On the contrary, those with strong intermediate-age star formation, namely SFR >0.2, are located above the least squares fit line (filled circles). We note that galaxies which had a conspicuous star formation during the past ~1–8 Gyrs lie above the continuous line, with the only exception being NGC 6822. It has a smaller number of PNe than expected for its mass. It might be due to the determination of its stellar mass which is particularly difficult because of the large extent of its halo (Weldrake, de Blok, & Walter 2003). Another aspect which might be suggested from Figure 5 is that all systems associated with M 31 (M 32, NGC 205, NGC 147, IC 10, with exception of NGC 185) and with the MW (SMC,
LMC) have enhanced 'recent' star formation, while several isolated systems have lower rates (Sextans A, Sextans B, Leo A, NGC 6822), suggesting that star formation might be enhanced by interaction with the giant galaxies.

In the lower panel, the total stellar mass of the galaxies is plotted versus the observed number of candidate PNe. Again a linear trend can be traced, but we note that only a lower limit to the intermediate-age mass can be estimated from this plot because the number of PNe might be not complete. The location in this diagram of IC 1613 and WLM, is in agreement with what we know about their star formation histories, showing a higher star formation during intermediate ages in IC 1613 than in WLM.

PNe are therefore confirmed to be useful evolutionary age tracers of the intermediate-age population. The presence of PNe is enough evidence for an intermediate-age population (Aparicio & Gallart 1994), and, in addition, the relationship of their number to the host galaxy mass gives information on the relative star formation history between different galaxies, where the same completeness in the search of PNe has been reached. These results agree with the those obtained by accurate SFH analysis (Mateo 1998).

6 SUMMARY AND CONCLUSIONS

In this paper we presented the search for PNe in three dwarf irregular galaxies belonging to the Local Group, or close to it: IC 1613, WLM, and GR 8. We discovered two new candidate PNe in IC 1613, one in WLM, and none in GR 8. Their number and their absolute magnitude were analyzed as a function of the SFH of the hosting galaxies. The number of PNe of these galaxies together with the number of PNe in the other LG galaxies are used to estimate the mass of intermediate-age population of each galaxy. This is compared with the SFR of the LG dwarf galaxies from 1 to 8 Gyr ago, finding that the number of PNe agrees with the results obtained by accurate SFH analysis and can therefore be used to constrain synthetic models of SFHs.

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Figure 5. Upper panel: the total stellar mass vs. the number of PNe within 4 mag from the cutoff of the PNLF in the galaxies where it was possible to extrapolate this value. Dwarf galaxies are marked with filled circles when SFR>0.2, and filled squares when SFR<0.2, according to Mateo (1998). Empty squares indicate galaxies with insufficient data available to study their SFHs. Triangles indicate large galaxies. The continuous line is the least squares fit. Lower panel: the total stellar mass of a galaxy expressed in M⊙ (from vdB00) vs. number of observed PNe (left vertical axis), which is proportional to the mass of the intermediate-age stellar population (right vertical axis).
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