Planetary Nebulae: A Universal Toolbox in the Era of Precision Astrophysics
Proceedings IAU Symposium No. 384, 2025
O. De Marco, A. Zijlstra & R. Szczerba, eds.
doi:10.1017/S1743921324000085

Towards Precision Cosmology With Improved PNLF Distances Using VLT-MUSE

George H. Jacoby[1], Robin Ciardullo[2], Martin M. Roth[3] and Magda Arnaboldi[4]

[1]NSF's NOIRLab, U.S.A.

[2]The Penn State University, U.S.A.

[3]Leibniz Institute for Astrophysics Potsdam (AIP), Germany

[4]European Southern Observatory

Abstract. We analyzed VLT/MUSE data for 20 galaxies in the ESO public archive to identify their systems' planetary nebulae (PNe). Using the differential emission line filter (DELF) technique, we performed photometry of the galaxies' PNe and determined their distances via the planetary nebula luminosity function (PNLF). Of the 16 galaxies for which a quality PNLF could be formed, two are isolated and more distant than 30 Mpc and therefore, relatively unaffected by Hubble Flow peculiar velocities. Using these data, we derived a Hubble Constant of 74.2 ± 7.2 (stat) ± 3.7 (sys) km s^{-1} Mpc^{-1}, a value that is similar to that found from other quality indicators (e.g., Cepheids, the tip of the red giant branch, and surface brightness fluctuations), but with a larger uncertainty due to the small number of galaxies. We describe how to improve PNLF measurements so that the precision of the technique is comparable to that of other quality distance indicators. We also describe a path forward in the era of ELTs that supersedes current techniques.

Keywords. Galaxies: distances, galaxies: individual, planetary nebulae

1. Introduction and motivation

The measurement of accurate and precise distances to astronomical objects, particularly external galaxies, has always posed a problem for astronomers. In the 1970s and 1980s, the notable era of the "The Hubble Controversy", the distance debate revolved around whether the Hubble Constant, H_0, was 50 or 100 km s^{-1} Mpc^{-1}, and there was limited discourse about any intermediate values (Jacoby et al. 1992). This factor of two uncertainty permeated all fields of extragalactic astronomy and was considered the most serious problem in cosmology. In fact, since the methodology and instrumentation of the time were not up to the task of resolving the Hubble Constant question, the literature was dominated by a few personalities rather than hard science. The field needed new ideas and techniques, and also new scientists. And, that transition did not occur until the 1990s and beyond.

Over the past two decades, measurement techniques have improved dramatically, so that H_0 values are now generally quoted to 1-2%. But this precision has brought about its own controversy: whether the measured distances to galaxies are consistent with the paradigm of the standard model. Inconsistencies at the $3-5\sigma$ level between measurements of H_0 based on the Cepheid calibration of the Type Ia supernova (Riess et al.

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https://doi.org/10.1017/S1743921324000085 Published online by Cambridge University Press

2022) and that from the microwave background (Planck Collaboration et al. 2020) have ushered in the era of "The Hubble Tension". If real, the discrepancy means that new physics, beyond ΛCDM cosmology, is needed to explain the universe (Kamionkowski & Riess 2023). Since other distance-ladder (Freedman et al. 2019; Garnavich et al. 2023) and non-distance-ladder (Pesce et al. 2020; Wong et al. 2020) techniques also suggest an H_0 discrepancy, it is once again the case that the distance scale is considered to be one of the most serious problems in cosmology.

Given what is at stake, new, precise (1-2%) techniques are needed to validate the results from Cepheids, and, since Cepheids are Population I objects, those methods must work in galaxies with recent star formation. The planetary nebula luminosity function (PNLF), as implemented by VLT/MUSE, is very promising in this regard (Roth et al. 2021; Jacoby et al. 2023). This paper presents a brief description of our work toward demonstrating that approach.

2. The PNLF method has matured

In the mid-1980s, the concept of using PNe as distance indicators seemed questionable at best, and was poorly received. Distances to Galactic PNe were almost impossible to measure to more than a factor of 2-3, and their morphologies and excitations are so diverse that their consideration as "standard candles" could not be taken seriously. Still, the physics of photoionization is relatively straightforward and common to all PNe, and a single PN was not being proposed as a standard candle: it was the bright-end cutoff of the luminosity function of an ensemble of sources that served as a standard. The lack of a complete theoretical basis for a universal bright-end cutoff did slow acceptance of the technique, but the excellent results obtained in the Local Group, NGC 5128, M81, and the Leo I Group, were hard to dispute (see the review by Ciardullo 2012).

However, beyond ∼10 Mpc, evidence emerged that the PNLF distances were too small by ~ 0.2 mag. Also, unexplained were the "overluminous" PNe appearing in galaxies at larger distances. This fueled speculation that the PNLF distances were being biased, perhaps by contamination from supernova remnants, (Kreckel et al. 2017), H II regions, background Lyα emitting galaxies (Ciardullo et al. 2002b), or even object superpositions (Chase et al. 2023).

Roth et al. (2021) demonstrated that most of these biases could be addressed using MUSE on the VLT. Specifically, the instrument's wide spectral coverage enables PNe to be separated from most other emission line objects via line ratios, in much the same way as the classic BPT diagram (Baldwin et al. 1981). Moreover, MUSE's $R \sim 2000$ spectral resolution allows blended objects to be resolved via their differing radial velocities, leaving any remaining blends to be dealt with using the methodology of Chase et al. (2023).

VLT/MUSE PNLF observations are greatly improved over the original concepts of narrow-band imaging (Ciardullo et al. 1989). The advantages come from utilizing (a) a "dynamically" defined very narrow-band differential emission line filter (DELF) with an effective bandpass of $\sim 3-5$ Å, (b) an 8 m versus a 4 m aperture, and (c) much-improved image quality (0.″6-0.″7 instead of 0.″9-1.″1). Ultimately, MUSE enables the unbiased application of the PNLF technique to ∼40 Mpc in both early and late-type galaxies, where previously the method had been limited to Population II systems within ~ 15 Mpc.

3. Results

We selected 20 galaxies from the ESO's science archive to help us explore the potential of MUSE for PNLF measurements. With a few exceptions, we chose galaxies having good seeing ($< 1.''0$), exposure times greater than an hour, distances between 20 and 35 Mpc,

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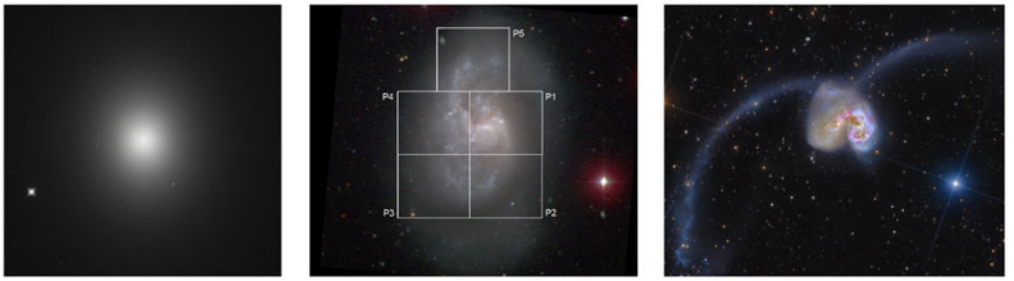


Figure 1. A sample of the galaxies analyzed in this project illustrating the variety of galaxy types. From left to right: the E1 elliptical M 49 (NASA), the Sc spiral NGC 1385 (ESO MUSE), and the interacting Antennae galaxies (Olsen/Subaru). For NGC 1385, the 5 MUSE fields that we used are outlined; the lack of field overlap introduced an additional zero-point error into the photometry.

and luminosities brighter than $M_V < -19$. We also had a preference for galaxies measured by other techniques and selected systems with a diverse range of morphologies and star-forming activity. This allowed us to explore environments where the PNLF works well or not at all. Figure 1 illustrates the diversity of our galaxy selection.

In four galaxies, the PNLF could not be used as a distance estimator: three of the galaxies had too few PNe to form a PNLF, and the fourth had a high inclination with significant and variable internal reddening. A sample of good and typical PNLFs is shown in Figure 2.

A lesson learned from this work is that the brightest magnitude of the PNLF needs to be populated by at least 50 PNe to form a well-defined PNLF (see the curve for NGC 1404). A second lesson learned from NGC 1433 is that each MUSE pointing must be carefully oriented to include a bright point source. Without such a source, photometric aperture corrections can not be measured to the precision necessary for distance scale work. If no bright star is available, the only alternative is to ensure the pointing overlaps a datacube with a bright PSF star, and there must be a number of sources in the regions of field overlap.

4. Distances and H_0

Figure 3 shows a histogram for our 16 galaxies with well-determined PNLF distances. The "cluster" of distances near 18 Mpc is the result of the large collection of MUSE archival data in the Fornax cluster. Two galaxies stand out. NGC 4355 and 6958 are the most distant galaxies yet measured with the PNLF. Both have distances greater than ~ 30 Mpc, both are early-type lenticulars, and both are relatively isolated, meaning their peculiar velocities should be small. The galaxies' radial velocities should therefore be representative of a largely unperturbed Hubble flow.

For these two galaxies, we derive PNLF distances of 32.9 ± 1.3 (for NGC 4355) and 36.2 ± 3.8 Mpc (for NGC 6958), with the large uncertainties driven by the relatively small number of PNe found in each system (24 and 15, respectively). Nevertheless, if we compare these numbers to the galaxies' recessional velocities, we obtain values for H_0 of 75.0 ± 9.6 and 69.2 ± 11.0 km s^{-1} Mpc^{-1} respectively. The weighted average of these two values, 74.2 ± 7.2 km s^{-1} Mpc^{-1} is quite encouraging, especially considering that it is based on archival data that were not optimized for distance scale studies.

Although the $\sim 10\%$ uncertainty is far higher than that derived from the Cepheid, tip of the red giant branch (TRGB) or surface brightness fluctuations (SBF) calibrations of SN Ia, this is mainly due to the targets being relatively small and not optimally

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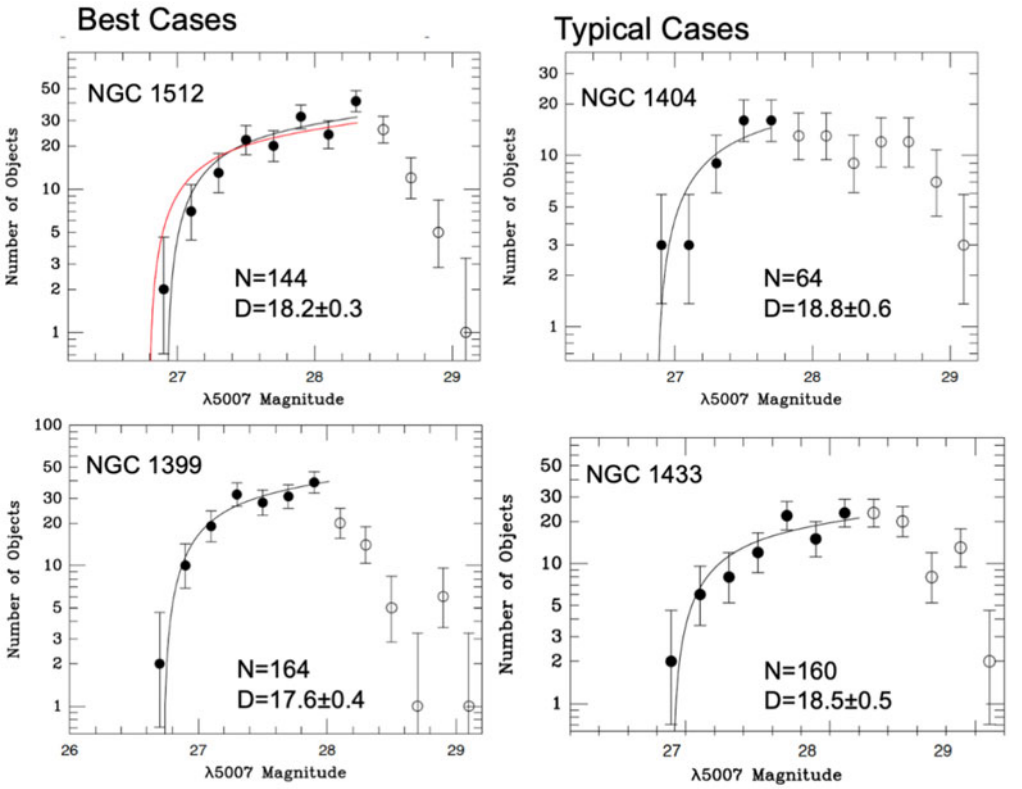


Figure 2. A sample of PNLFs. For NGC 1512, the red curve is the nominal fit to the reference PNLF equation (Ciardullo et al. 1989) and the black curve is the fit to that equation as modified for superpositions (Chase et al. 2023).

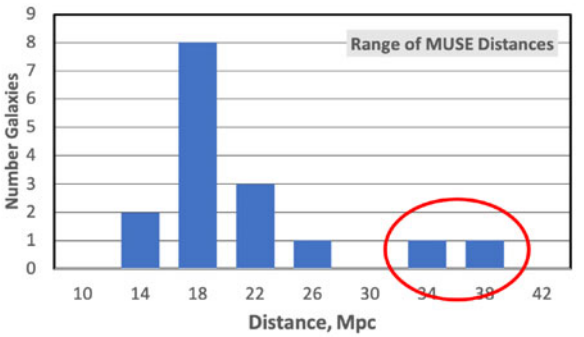


Figure 3. A histogram of the distances derived for the 16 galaxies for which a reasonable PNLF could be formed from the MUSE archive collection. NGC 4355 and 6958 are circled in red.

observed. Moreover, they are just two galaxies. In our new MUSE/PNLF dataset, we see no evidence for distance biases, so, in principle, observations of 25-30 galaxies beyond $\sim$30 Mpc can be expected to drive the average error down by a factor of 5, to 2% or better.

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Table 1. PNLF compared with Cepheids, TRGB and SBF.

Method	N(galaxies)	Difference
Cepheids	1	+7%
TRGB	3	+4%
SBF	8	−9%

Table 2. PNLF comparison in specific cases.

Galaxy	NGC 1404	NGC 4038/9
PNLF/Cepheid	...	+7.5%
PNLF/TRGB	+0.5%	+4.2%
PNLF/SBF	−7.4%	...

5. Precision

Since there is no collection of test galaxies with *a priori* known distances, the true precision and accuracy of a distance technique is difficult to derive. Can the PNLF really be used to obtain a 2% error on H_0? Note that this goal represents the precision for an ensemble of measurements, not for any one object, and it is a goal that has not been convincingly achieved for any method.

The usual approach to understanding the precision of a method is to compare it against other "gold standard" techniques. Cepheids and TRGB are currently held in the highest regard, with SBF a close third. When we compare our PNLF results to these methods, the results are promising but not yet compelling, as the sample is small. This is summarized in Table 1. Unfortunately, only one galaxy has a Cepheid distance and it is a somewhat peculiar object: NGC 4038/39, otherwise known as the "Antennae Galaxy". Nevertheless, the PNLF distance is within 7% of the Cepheid measurement, well within the combined errors of the two methods.

The TRGB comparison is based on 3 galaxies and the average difference is quite small, with the PNLF generating distances that are, on average 4% further. The 9% difference for the 8 SBF galaxies may seem problematic at first, but it has the opposite sign for that of the Cepheid and TRGB comparisons. Moreover, this difference is considerably smaller than previous checks between these methods (Ciardullo et al. 2002a) where the average difference was 15%. As shown by Ciardullo et al. (1993, 2002a), the fact that PNLF distances are systematically shorter than those of the SBF is consistent with the idea that the calibration galaxies used by the two methods have more internal extinction than the techniques' program galaxies.

For the 16 galaxies in our sample, the internal uncertainties of the PNLF fits are typically 6% and the best targets exhibit errors as small as 4%. The latter galaxies are usually early-type systems containing large numbers of bright PNe that were observed in a manner that was almost optimal for PNLF distance scale studies (see § 6). Table 2 provides a 4-way check for two of these well-observed systems. There is no reason why targeted observations for PNLF distances cannot always achieve this level of precision ($< 4\%$).

6. Achieving H_0 with 2% precision

With a sample of 25–30 well-observed galaxies, the PNLF can deliver a good measurement of H_0 directly from their distances in the relatively unperturbed Hubble flow. Alternatively, the PNLF can calibrate SN Ia luminosities in systems that are not amenable to Cepheid and/or TRGB analyses, thereby linking the technique to measures of the distant universe.

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For PNLF measurements to be successful, they must be carefully planned, as (a) the seeing must be better than 0.″75, (b) the galaxies chosen must be isolated E/S0 systems with $M_V < -19.5$, (c) each observation must contain a bright star for PSF determination (or at least overlap a frame that does have a PSF star in order to bootstrap the photometric zero point), and d) the exposure times and enclosed galaxy luminosity must be sufficient to identify 50–100 PNe in the top magnitude of the luminosity function.

Finally, it should be noted that the importance of a single PN to a galaxy's PNLF depends strongly on its luminosity: the brighter the PN, the more weight it carries in defining the system's PNLF cutoff. This fact, coupled with the rarity of bright PNe, means that it is critically important to continually improve our knowledge of the true shape of the function's bright-end cutoff (Jacoby et al. 2023).

7. Future steps

One underlying issue that has slowed the acceptance of PNLF distances is the lack of a complete theoretical understanding of the shape of the luminosity function and its resilience to population variances. Metallicity corrections may be required for some galaxies, and while the response of the PNLF cutoff to oxygen abundance has been modeled (Dopita et al. 1992; Schönberner et al. 2010), the empirical data must be improved (Ciardullo & Jacoby 1992).

Understanding the cutoff's constancy with population age is trickier, though it appears to be related to dust generated within the PN progenitors (Ciardullo & Jacoby 1999; Davis et al. 2018). Briefly put: the PNe from younger populations derive from more massive progenitors which eject more gas and dust on the AGB. The greater amount of ejected dust, and the shorter time it has to disperse before ionization, compensates for the higher luminosities of the central stars that drive the observed [O III] brightness. This correlation between progenitor age and intrinsic extinction has been independently calibrated in M31's disc via their age-velocity-dispersion relation (Bhattacharya et al. 2019).

Looking toward the era of Extremely Large Telescopes with MUSE-like integral-field spectrographs, the PNLF can be extended 2–3 times further. At those distances, cosmic velocity errors will not dominate the error as they do at 35 Mpc. Relatively fewer galaxies will be needed to a achieve high precision measurement of H_0.

8. Acknowledgements

The NSF supported this work through grant AST2206090. Based on data obtained from the ESO Science Archive Facility with DOI(s): https://doi.org/10.18727/archive/41 and https://doi.org/10.18727/archive/42. This work has made use of the SIMBAD database, operated at CDS, Strasbourg, France, and of the NASA/IPAC Extragalactic Database (NED), which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. The Institute for Gravitation and the Cosmos is supported by the Eberly College of Science and the Office of the Senior Vice President for Research at the Pennsylvania State University.

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