Planetary Nebulae: Multi-Wavelength Probes of Stellar and Galactic Evolution
Proceedings IAU Symposium No. 323, 2016
X. Liu, L. Stanghellini & A. Karakas, eds.

doi:10.1017/S1743921317000709

The halo of M49 and its environment as traced by planetary nebulae

Johanna Hartke[1], Magda Arnaboldi[1], Alessia Longobardi[2,3], Ortwin Gerhard[3], Ken Freeman[4] and Sadanori Okamura[5]

[1]European Southern Observatory, Karl-Schwarzschild-Str. 2, 85748 Garching, Germany, email: [jhartke;marnabol]@eso.org

[2]Kavli Institute for Astronomy and Astrophysics, Peking University, 5 Yiheyuan Road, Beijing 100871, P. R. China, email: alongobardi@pku.edu.cn

[3]Max-Planck-Institut für Extraterrestrische Physik, Giessenbachstrasse, 85748 Garching, Germany, email: gerhard@mpe.mpg.de

[4]RSAA, Mt. Stromlo Observatory, 2611, Canberra, Australia, email: Kenneth.Freeman@anu.edu.au

[5]Department of Advanced Sciences, Faculty of Science and Engineering, Hosei University, 184-8584 Tokyo, Japan, email: sadanori.okamura@hosei.ac.jp

Abstract. We investigate the stellar halo of the nearby elliptical Virgo-cluster galaxy M49 using Planetary Nebulae (PNe). M49 is the second-brightest galaxy of the Virgo cluster and is at the center of the Virgo subcluster B. We present an extended catalogue extracted from a narrow-band survey carried out with Subaru's Suprime Cam, consisting of 735 PNe down to a limiting magnitude of $m_{5007} = 29.3$. This PNe population traces the halo out to 155 kpc from the galaxy's center, which provides accurate measurement of the luminosity-specific PN-number (α-parameter) in the inner and outer regions of M49's halo. We are also able to determine the morphological variation of the planetary nebulae luminosity function (PNLF), that may trace different parent stellar populations. This enables us to identify the transition from the PN-scarce, possibly metal-rich, galaxy halo to the PN-rich, metal-poor, outer component.

Keywords. galaxies: clusters: individual (Virgo), galaxies: elliptical and lenticular, cD, galaxies: individual (M49), planetary nebulae: general

---

1. Introduction

In the current paradigm of hierarchical structure formation, galaxies build-up to their current size by a two-phase process consisting of in-situ star formation and then further growth through mergers and accretion of smaller structures (e.g. Oser *et al.*, 2012). These accretion events leave long-lasting signatures in the galaxies' halos which can be identified in the kinematic phase-space or in the density distribution of stars. Numerical simulations predict that a significant fraction of halo stars have been accreted in the most massive galaxies (e.g. Cooper *et al.*, 2013). In order to better understand the late stages of galaxy formation, we need to identify accretion events and their time scales.

M49 (NGC 4472) is the brightest galaxy in the Virgo Cluster. It is surrounded by a diffuse halo that contains a layered system of shells that is suggestive of a hierarchical build-up (Mihos *et al.*, 2005, Janowiecki *et al.*, 2010). Furthermore, there is ongoing accretion of the dwarf irregular galaxy VCC 1249 (Arrigoni Battaia *et al.*, 2012). Extended multi-band photometry of the halo provides evidence for an extended, blue halo (Mihos *et al.*, 2013). Single stellar population models predict corresponding metallicities from [Fe/H] $\simeq -1.0$ to -1.5 (Bruzual & Charlot, 2003). This low metallicity and the large size of this halo are in conflict with predictions from conventional hierarchical assembly:

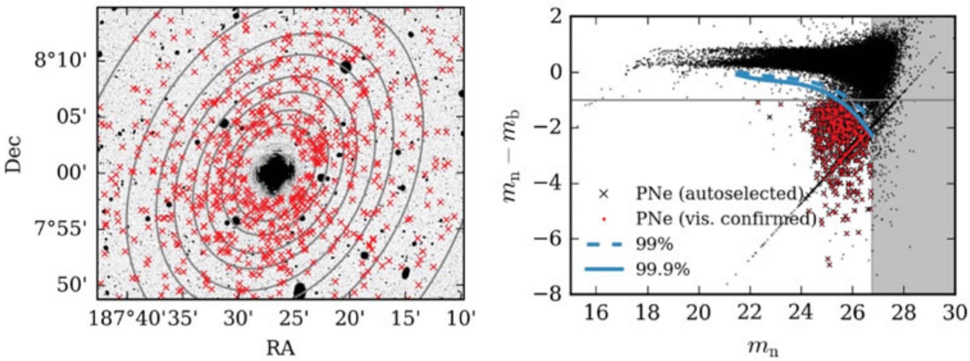

Figure 1. *Left:* [OIII] image of M49 with PN candidates indicated by red crosses. Elliptical bins with $PA = -31°$ and $\epsilon = 0.28$ (Kormendy *et al.*, 2009) are spaced such that they contain ~ 70 objects in each bin. *Right:* CMD of automatically detected sources. Visually confirmed PN candidates are plotted with red dots. The solid blue line indicates the region where 99.9% of a simulated continuum population with no colour excess would lie.

progenitors which are expected to have built a M49-sized halo would have contributed higher metallicities than the one measured in M49's outer halo (see e.g. Tremonti *et al.* (2004) for the mass-metallicity relation for galaxies).

Planetary nebulae (PNe) are the only single *stellar* tracers which can be used to study the halos of galaxies at the distance of the Virgo Cluster. In the following we present a new, homogeneous and statistically complete sample of PNe in M49's extended halo.

2. PNe selection

We have obtained deep [OIII] and V-band images with the Suprime-Cam at the 8.2m Subaru telescope. The mosaic camera covers an area of $34' \times 27'$, thus M49's halo can be observed out to a major-axis distance of 155 kpc. We select PNe using the on-off band technique, making use of two characteristic features of the PN spectrum: the bright [OIII]5007 Å emission and the absence of a continuum. PNe can thus be identified through their on-band [OIII] emission and absence of emission on the broad-band V-image. We use an automatic selection procedure, which selects point-like candidates with [OIII] - V colour excess (Arnaboldi *et al.*, 2002, 2003). The left panel of Fig. 1 shows the selected 735 PN candidates which have been detected within the limiting magnitude of $m_{[\mathrm{OIII,lim}]} = 29.3$. The limiting magnitude of this survey is defined as the magnitude where the recovery fraction of a simulated PN population drops below 50%. We also use this simulated population in order to evaluate the photometric and detection completeness of our survey. The right panel of Fig. 1 illustrates the colour-magnitude diagram (CMD) and the location where the PN candidates are selected.

3. The PN number density distribution and α-parameters

Previous studies have shown that the PN number density follows stellar light in early-type galaxies (Coccato *et al.*, 2009, Cortesi *et al.*, 2013, Longobardi *et al.*, 2013). The stellar light is characterized by a Sérsic profile out to $r \sim 915''$ (Kormendy *et al.*, 2009) after which it starts to flatten (Capaccioli *et al.*, 2015). The PN number density profile follows the stellar light closely, and it flattens already beyond a radius $r \sim 730''$ (Hartke *et al.*, 2016). The flattening is likely due to the presence of an additional component

https://doi.org/10.1017/S1743921317000709 Published online by Cambridge University Press

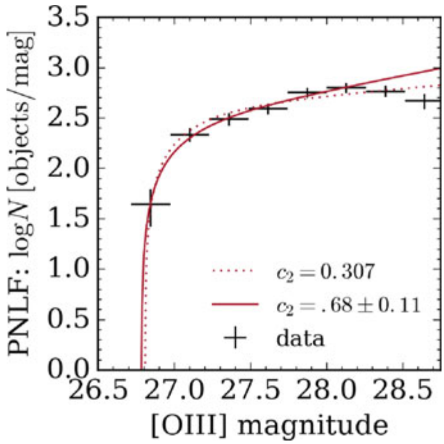

Figure 2. PNLF of M49 corrected for completeness and Ly-α contamination.

associated with the outer halo, e.g a contribution from intragroup light (IGL) from the Subcluster B at whose center M49 resides.

The total number of PNe N_{PN} and the total bolometric luminosity L_{bol} of the underlying stellar population are related through the luminosity-specific PN number, also known as α-parameter: $N_{\mathrm{PN}} = \alpha L_{\mathrm{bol}}$. We determine the α-parameter in the two radial regimes by fitting a two-component model for the PN number density; one population follows a Sérsic-like radial profile and the contribution from the IGL is constant with radius. The best-fit model is found to have a PN-yield that varies, with the outer halo contributing roughly three times more PN than the inner halo. The higher abundance of PNe in the outer regions is likely due to the presence of PNe associated with the surrounding IGL. A higher PN-yield was also observed in M87, where Virgo's intracluster PNe were kinematically identified in Longobardi *et al.* (2015) after having observed a flattened number density profile (Longobardi *et al.*, 2013).

4. The PNLF of M49

We also characterize M49's PN sample by its luminosity function (PNLF) and we use the analytical formula that was introduced by Longobardi *et al.* (2013) to fit the PNLF of M87:

$$N(M) \propto e^{M c_2}(1 - e^{3(M^\star - M)}). \tag{4.1}$$

This is the generalized form of the PNLF that allows for variation of the faint-end slope by having c_2 as a free parameter. The Ciardullo *et al.* (1989) formula is then a particular case with $c_2 = 0.307$. Because of the empirical evidence for a bright cut-off consistent with a absolute magnitude $M^\star = -4.51$ (Ciardullo *et al.*, 2002), the PNLF can be used as a secondary distance indicator. Using the generalized formula, we determine a distance modulus of $\mu_{\mathrm{PNLF}} = 31.29^{+0.07}_{-0.08}$ for M49, which agrees with the distance determined from Surface Brightness Fluctuations (SBF, $\mu = 31.17 \pm 0.07$, Mei *et al.*, 2007). Several authors have debated about the discrepancy between SBF and PNLF distances (e.g Mendez *et al.*, 2016 at the IAUS 323, Ciardullo *et al.*, 2002, Ciardullo, 2012). We believe that this discrepancy may arise because of a contamination of the sample by Ly-α emitters at redshift $z = 3.1$, which is statistically corrected for in the M49 sample (see Hartke *et al.* (subm.) for further details). The Ly-α-corrected PNLF is shown in Fig. 2.

Another characteristic of the analytic PNLF is its slope, which is set by the parameter c_2. Steeper slopes are measured for PN populations with older parent stars (e.g Ciardullo *et al.*, 2004, Longobardi *et al.*, 2013). We fit a PNLF to the two radial regimes identified in the previous section and determine a steeper PNLF slope in the outer region compared to the inner one.

We then investigate the PNLF in four quadrants in the inner halo in order to trace local variation of the PNLF. We find that one of the quadrants has a significantly flatter PNLF slope than the other three. The flatter slope is likely due to a young, bright population of PNe, which points to an accretion event. While no substructure is prominent in the light at the location of the PN-population with flatter PNLF, it is reasonable to associate them with stars that were tidally displaced during the accretion of VCC 1249.

5. Conclusions and Outlook

We have presented a PN-survey with unprecedented coverage of the halo of M49. We are able to trace the transition between galaxy and intragroup light based on the flattening of the PN number density profile compared to the light. Our fit of a two-component model points towards an IGL population with a three-times higher α-parameter compared to the main halo. We have accurately determined the distance to M49 using the bright cut-off of the PNLF and have resolved the PNLF-SBF distance discrepancy at least for this object. The morphology of the PNLF shows variation that points us to a change in the physical properties (like age, metallicity) of the stellar populations, which is likely to arise from the accretion of VCC 1249. Next, we want to obtain high-resolution spectra of the PNe in order to kinematically map M49's extended halo. We will then be able to disentangle intragroup and halo PNe and identify substructures from accretion events in the PN-velocity phase-space.

References

Arnaboldi, M., Aguerri, J. A. L., Napolitano, N. R., *et al.* 2002, *AJ*, 123, 760
Arnaboldi, M., Freeman, K. C., Okamura, S., *et al.* 2003, *AJ*, 125, 514
Arrigoni Battaia, F., Gavazzi, G., Fumagalli, M., *et al.* 2012, *A&A*, 543, A112
Bruzual, G. & Charlot, S. 2003, *MNRAS*, 344, 1000
Capaccioli, M., Spavone, M., Grado, A., *et al.* 2015, *A&A*, 581, A10
Ciardullo, R., Jacoby, G. H., Ford, H. C., & Neill, J. D. 1989, *ApJ*, 339, 53
Ciardullo, R., Feldmeier, J. J., Jacoby, G. H., *et al.* 2002, *ApJ*, 577, 31
Ciardullo, R., Durrell, P. R., Laychak, M. B., *et al.* 2004, *ApJ*, 614, 167
Ciardullo, R. 2012, *ApSS*, 341, 151
Coccato, L., Gerhard, O., Arnaboldi, M., *et al.* 2009, *MNRAS*, 394, 1249
Cooper, A. P., D'Souza, R., Kauffmann, G., *et al.* 2013, *MNRAS*, 434, 3348
Cortesi, A., Merrifield, M. R., Coccato, L., *et al.* 2013, *MNRAS*, 432, 1010
Hartke, J., Arnaboldi, M., Longobardi, A., *et al.* 2016, *A&A*, subm.
Janowiecki, S., Mihos, J. C., Harding, P., *et al.* 2010, *ApJ*, 715, 972
Kormendy, J., Fisher, D. B., Cornell, M. E., & Bender, R. 2009, *ApJS*, 182, 216
Longobardi, A., Arnaboldi, M., Gerhard, O., *et al.* 2013, *A&A*, 558, A42
Longobardi, A., Arnaboldi, M., Gerhard, O., & Hanuschik, R. 2015, *A&A*, 579, A135
Mei, S., Blakeslee, J. P., Côté, P., *et al.* 2007, *ApJ*, 655, 144
Mendez, R. H. 2016, ArXiv e-prints 1610.08625
Mihos, J. C., Harding, P., Feldmeier, J., & Morrison, H. 2005, *ApJL*, 631, L41
Mihos, J. C., Harding, P., Rudick, C. S., & Feldmeier, J. J. 2013, *ApJL*, 764, L20
Oser, L., Naab, T., Ostriker, J. P., & Johansson, P. H. 2012, *ApJ*, 744, 63
Tremonti, C. A. *et al.* 2004, *ApJ*, 613, 898

https://doi.org/10.1017/S1743921317000709 Published online by Cambridge University Press

Discussion

MENDEZ: Jacoby *et al.* (1990) got a smaller PNLF distance to M49. Did you check your magnitudes against theirs for any objects you may have in common?

HARTKE: We have not cross-match the individual catalogues. We wish to commenton the different sample sizes ∼30 PNe vs. ∼730 in our sample. The difference in the bright cut-off is probably due to different ways of accounting for contamination from $z = 3.1$ Ly a emitters, which also have strong 5007 Aemission.

TORRES-PEIMBERT: How did you correct for the Ly alpha galaxy population?

HARTKE: We statistically correct for Ly-a emitters at $z = 3.1$ based on their luminosity function as determined by Gronwall *et al.* (2007). In every mag-binwe subtract the number of expected Ly-a emitters from the completeness-corrected number of PNe.