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The planetary nebulae luminosity function and distances to the Virgo, Hydra I, and Coma Clusters

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Abstract. The luminosity function of planetary nebula populations in galaxies at distances within 10–15 Mpc exhibits a cut-off at bright magnitudes and a functional form that is observed to be invariant among different galactic morphological types. Therefore, it is used as a secondary distance indicator applicable to both early- and late-type galaxies. Recent deep surveys of planetary nebula populations in brightest cluster galaxies (BCGs) seem to indicate that their luminosity functions deviate from those observed in the nearby galaxies. We discuss the evidence for such deviations in the Virgo Cluster, and indicate which physical mechanisms may alter the evolution of a planetary nebula envelope and its central star in the halo of BCGs. We then discuss preliminary results for distances to the Virgo, Hydra I, and Coma Clusters based on the observed planetary nebulae luminosity functions.

Keywords. stars: AGB and post-AGB, planetary nebulae: general, galaxies: elliptical and lenticular, galaxies: cD

1. Introduction

Most of the stars in the mass range between 1 and 8 $M_\odot$ go through the planetary nebula (PN) phase during the final stages of their lives, before they become white dwarfs. During this phase, the nebular shell of a PN converts the ultraviolet (UV) ionizing photons into various emission lines, from the UV to the optical and the near-infrared. Up to 15% of the UV energy emitted by the central star is re-emitted in the [O III]λ5007Å line, which provides the brightest optical emission of PNe (Dopita *et al.* 1992).

When observed in our own Milky Way, a PN's shells and [O III] emission are spatially resolved. In M31 and beyond, PNe are spatially unresolved sources of green light. Thus, the full [O III] flux, F_{5007}, emitted by a PN shell can be integrated and an m_{5007} magnitude is computed as (Jacoby 1989)

$$m_{5007} = -2.5 \log F_{5007} - 13.74. \tag{1.1}$$

For PN populations in external galaxies, we can derive the PN luminosity function (PNLF). The PNLF was measured for PN populations in early- and late-type galaxies within 10–15 Mpc distance (for a review, see Ciardullo *et al.* 2002) with the following properties:

- The PNLF shows a cut-off at the bright end, at an absolute magnitude of $M^* = -4.51$ mag.
- The shape of PNLF *and* the cut-off at bright magnitudes are observed to be invariant in galaxies of different morphological types, either star-forming or quiescent, within a distance of 10–15 Mpc.

Thus, the PNLF can be used efficiently as a secondary distance indicator and plays an important role in investigations of systematic biases, because it represents one of the few methods that can be applied to both early- and late-type galaxies.

The PNLF has been shown empirically (Ciardullo *et al.* 1998) to obey the analytical formula

$$N(m_{5007}) = C \times e^{0.307 m_{5007}} \times [1 - e^{3(m^* - m_{5007})}], \tag{1.2}$$

where m^* is the apparent magnitude of the bright cut-off. This formula combines the observed behavior at the bright end, which is believed to originate from the most massive, $M_{\rm core} \simeq 0.7$ $\mathrm{M}_\odot$, surviving stellar cores (Ciardullo *et al.* 1989; Marigo *et al.* 2004), and the slow PN fading rate caused by the envelope's expansion at the faint end (Henize & Westerlund 1963).

It is an open question whether more physics is required to describe PN populations in massive galaxies than what is captured by the analytical formula of Eq. (1.2).

2. Physics of the PNLF

The theoretical basis for the $N(m_{5007})$ analytical formula is a population of uniformly expanding, homogeneous, spherical PNe ionized by non-evolving central stars. The observed invariance of M^* also seems to indicate that the most massive surviving stellar cores all have the same mass, regardless of the age and metallicity of the parent stellar population. Each of these hypotheses may turn out to be violated in different environments, and we discuss each possibility in turn.

Constancy of M^* – A PN's peak flux is proportional to its core mass (Vassiliadis & Wood 1994). A PN's core mass is proportional to its turn-off mass (Kalirai *et al.* 2008). The turn-off mass of a stellar population decreases with age (Marigo *et al.* 2004). Simple stellar population theory would then predict that the absolute magnitude of the PNLF at the bright cut-off should become fainter already in a 1 Gyr-old population, and decrease by up to four magnitudes in a 10 Gyr-old stellar population.

Uniformly expanding, homogeneous spherical shells – The nebular shell may not be spherical (as observed for many Milky Way PNe), not expanding uniformly, and not optically thick. The presence of a hot interstellar medium (ISM) in evolved stellar populations may also effect the amount of mass loss during the AGB evolution and the properties of the ionized PN shell (Dopita *et al.* 2000; Villaver & Stanghellini 2005). The interaction between nebular shell and hot gas may also decrease the visibility lifetime of a PN, $\tau_{\rm PN}$, which in turn decreases the total number of PNe associated with a given bolometric luminosity emitted by the parent stellar population (Buzzoni *et al.* 2006).

Non-evolving central star – Simple stellar population theory predicts low-mass cores, $M_{\rm core} \leqslant 0.55$ $\mathrm{M}_\odot$ (Buzzoni *et al.* 2006) in old stellar populations, such as in the M87 halo (Williams *et al.* 2007). For such low-mass cores, $\tau_{\rm PN}$ may be shorter than 3×10^4 yr (Buzzoni *et al.* 2006), because the time required for excitation of the nebular envelope increases, and by the time it happens, the density in the nebular shell may be too low for any significant [OIII] emission to be generated. Furthermore, part of the stellar population with $M_{\rm core} \sim 0.52$ $\mathrm{M}_\odot$ may skip the PN phase entirely (Blöcker 1995). These evolved stars may provide an enhanced contribution to the hotter horizontal branch (HB) and

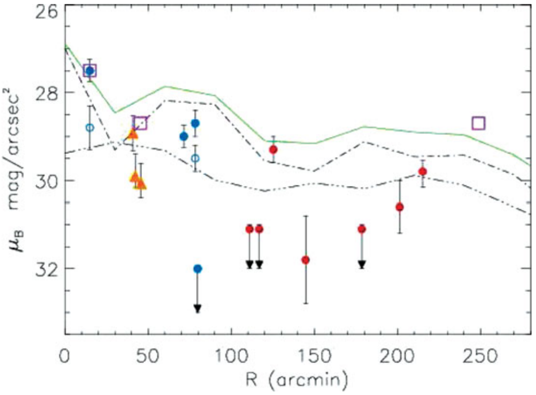

Figure 1. Surface brightness (SB) measurements of diffuse light in the Virgo fields (points) compared with the SB profile of the Virgo galaxies averaged in annuli (lines); radial distances are computed with respect to M87. The continuous line represents the radial SB profile of light in Virgo galaxies from Binggeli *et al.* (1987). The dot-dashed and double dot-dashed lines correspond to the SB profile associated with giants and dwarf galaxies, respectively. The blue (darker) solid dots show the SB measurements in the Virgo core. The open circles at distances of $10'$ and $80'$ indicate the ICL SB computed from IPNe that are not bound to galaxy halos. The triangles represent the SB of the ICL based on intracluster RGB star counts (Williams *et al.* 2007; and references therein). The red solid dots at distances greater than $80'$ show several SB measurements and arrows indicate their upper limits. The magenta open squares indicate the SB average values μ_B at 15, 50, and 240 arcmin computed from the measurements of Feldmeier *et al.* (2004); the measurements at $240'$ are close to M49. The diffuse light is concentrated on M87 and M49, with a sharp decrease at a distance of $80' = 0.4$ Mpc. (From Castro-Rodriguez *et al.* 2009)

post-HB evolution (Greggio & Renzini 1990), as directly observed in M32 and in the bulge of M31 (Brown *et al.* 1998, 2000).

Physical conditions which violate the hypotheses embedded in the analytical formula $N(m_{5007})$ may particularly occur in the halos of BCGs at the centers of massive clusters, because their stellar populations are old and immersed in a high-density intracluster medium. We then expect to find deviations of the observed PNLFs for these systems. The closest of these is the BCG galaxy in the Virgo cluster, M87. Similar physical conditions are expected for PNe in environments like NGC 3311 in the Hydra I cluster, and for the Coma cluster BCGs.

3. The PNLF in the M87 outer halo

The nearby clusters play a very important role in the cosmological distance ladder. The measurement of the distance to the Virgo Cluster by the Key Project team was crucial for the determination of the Hubble constant. Several projects have aimed at measuring the PNLF distance to the Virgo elliptical galaxies (for a review, see Ciardullo *et al.* 2002). The most extended PN survey in the M87 halo was carried out by Ciardullo *et al.* (1998), covering a $16' \times 16'$ field centered on M87.

The empirical PNLF measured in the M87 halo based on a sample of 338 PNe deviates significantly from the analytical formula for a distance modulus of $(m - M) = 30.79$ mag (Ciardullo *et al.* 1998). The deviations are such that (i) the PNLF shape is different for the inner $< 4'$ and the outer regions $> 4'$; the PN candidates in the halo have brighter m_{5007} magnitudes than the cut-off expected for $(m - M) = 30.79$ mag, and (ii) the PNLF for the outer sample is not drawn from a population that follows Eq. (1.2), at the

99% confidence level according to Kolmogorov–Smirnov tests. Originally, these PNLF deviations were explained in terms of a uniform intracluster PN (IPN) population, which extended 2 Mpc in front of the M87 halo PN population, so that the overluminous PNe could be explained as IPNe.

There is some tension in this proposed scenario. Spectroscopic follow-up of PNe bound to the M87 halo showed that these PNe have a brighter cut-off, $m^* = 26.2$ mag, than PNe in the inner regions, $m^* = 26.35$ mag (Arnaboldi *et al.* 2008). In addition, the extended survey carried out by Castro-Rodriguez *et al.* (2009) showed that the IPN population in the Virgo Cluster is associated with its densest regions, and IPNe extend to at most 0.4 Mpc in front of M87. In Fig. 1 we show the surface brightness profile of the intracluster luminosity (ICL) in the Virgo cluster; it shows that the ICL and IPN population are concentrated on M87 and on the densest regions of the cluster.

In 2010 we started a new project to survey PNe in M87, covering the entire halo out to 150 kpc. It entails an imaging survey with *Subaru*/SuprimeCAM, with the aim to cover 0.5 deg^2 in the M87 outer halo, and spectroscopic follow-up with *VLT*/FLAMES of selected candidates. PN candidates are identified using deep [O III] and off-band V images: they are selected as point-like [O III] sources with a color excess [O III] $-V = -1$, and no continuum (Arnaboldi *et al.* 2002). The SuprimeCAM observations for the PN survey in M87 were taken with a total exposure time in the narrow-band [O III] filter of approximately 4 hr, and a total exposure time in the off-band (V band) of ∼1 hr, for each pointing. Analysis of the data is ongoing; the properties of the PNLF from this extended PN sample, both in area and depth, will be presented by Longobardi *et al.* (in prep.).

4. Detecting PNe beyond Virgo

The brightest PNe in the Hydra I cluster at 50 Mpc distance have fluxes of 7.8×10^{-18} erg s^{-1} cm^{-2} (~ 7 photons min^{-1} on an 8 m telescope). In the Coma Cluster, fluxes are four times fainter. These very faint fluxes cannot be detected using a narrow-band filter, because the sky noise in a 30–40 Å spectral range centered on the redshifted [O III] PN emission is of the same order as the signal we want to detect. A step forward for the detection of PNe in elliptical galaxies in clusters at distances greater than 15 Mpc is the Multi Slit Imaging Spectroscopy Technique (MSIS). MSIS is a blind search technique, which combines a mask of parallel multiple slits with a narrow-band filter, centered on the redshifted [O III]λ5007Å line at the Hydra I/Coma mean systemic velocity, to obtain spectra of all PNe that lie behind the slits (Gerhard *et al.* 2005). The sky noise at the PN emission line now comes from a spectral range of only a few Å, depending on slit width and spectral resolution (Arnaboldi *et al.* 2007). Several tens of PNe have been detected using MSIS observations in the Hydra I (Ventimiglia *et al.* 2011) and Coma (Gerhard *et al.* 2007) Clusters.

We can then use the PNLF from the MSIS data sets to determine the distances to Coma and Hydra I relative to the Virgo Cluster, which may reduce systematics errors in the distance measurements to these clusters. This is important because several methods for measuring cosmological distances (i.e., the Fundamental Plane, high-z supernovae) rely on the distance to the Coma Cluster for their zero point.

Because PNe can be best observed for BCGs in these clusters, we need more advanced models for the PNLF (e.g., Méndez *et al.* 2008; see also the discussion in Section 2). Then we need to account for the through-slit convolution and convolution with photometric errors, as well as completeness corrections (see Ventimiglia *et al.* 2011). Next, the cumulative PNLF is a direct distance indicator that can be used to derive the distances to clusters beyond Virgo.

5. Preliminary results

Preliminary distance moduli and distances based on the PNLF and MSIS samples are

- Virgo $(m - M)_0 \simeq 30.8$ mag; $D_{\rm Virgo} \simeq 15$ Mpc;
- Hydra $(m - M)_0 \simeq 33.5$ mag; $D_{\rm Hydra\ I} \simeq 3.43 \times D_{\rm Virgo} = 51.5$ Mpc;
- Coma $(m - M)_0 \simeq 34.9$ mag; $D_{\rm Coma} \simeq 6.51 \times D_{\rm Virgo} = 97.7$ Mpc

The next steps of this project include

- use of the observed PNLF in the M87 halo (Longobardi *et al.*, in prep.) to test models for the PNLF in old stellar populations, including effects on AGB evolution and ionization of PNe caused by the presence of a hot ISM.
- enlarging the MSIS sample of PNe in Coma by including the PN samples from two additional fields (Arnaboldi *et al.*, in prep.).
- carrying out extensive simulations for MSIS (through-slit convolution, convolution with photometric errors, completeness corrections) and the effects of error estimates on the resulting distances (Gerhard *et al.* in prep.).

The project of determining distances to clusters out to Coma using the PNLF is entering into a new, exciting, phase!

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References

Arnaboldi, M., Doherty, M., Gerhard, O. E., *et al.* 2008, *ApJ*, 674, L17
Arnaboldi, M., Gerhard, O. E., Okamura, S., *et al.* 2007, *PASJ*, 59, 419
Arnaboldi, M., Aguerri, J. A. L., Napolitano, N. R., *et al.* 2002, *AJ*, 123, 760
Binggeli, B., Tammann, G. A., & Sandage, A. 1987, *AJ*, 94, 251
Blöcker, T. 1995, *A&A*, 299, 755
Brown T. M., Ferguson H. C., Stanford S., *et al.* 1998, *ApJ*, 504, 113
Brown T. M., Bowers C. W., Kimble R. A., *et al.* 2000, *ApJ*, 532, 308
Buzzoni, A., Arnaboldi, M., & Corradi, R. 2006, *MNRAS*, 368, 877
Castro-Rodriguez, N., Arnaboldi, M., Aguerri, J. A. L., *et al.* 2009, *A&A*, 507, 621
Ciardullo, R., Feldmeier, J. J., Jacoby, G. H., *et al.* 2002, *ApJ*, 577, 31
Ciardullo, R., Jacoby, G. H., Feldmeier, J. J., & Bartlett, R. E. 1998, *ApJ*, 492, 62
Ciardullo, R., Jacoby, G. H., Ford, H. C., & Neill, J. D. 1989, *ApJ*, 339, 53
Dopita, M., Massaglia, S., Bodo, G., *et al.* 2000, *ASP Conf. Ser.*, 199, 423
Dopita, M., Jacoby, G. H., & Vassiliadis, E. 1992, *ApJ*, 389, 27
Feldmeier, J. J., Ciardullo, R., Jacoby, G. H., *et al.* 2004, *ApJ*, 615, 196
Gerhard, O. E., Arnaboldi, M., Freeman, K. C., *et al.* 2007, *A&A*, 498, 815
Gerhard, O. E., Arnaboldi, M., Freeman, K. C., *et al.* 2005, *ApJ*, 621, L93
Greggio, L. & Renzini, A. 1990, *ApJ*, 364, 35
Jacoby, G. H. 1989, *ApJ*, 339, 39
Henize, K. G. & Westerlund, B. E. 1963, *ApJ*, 137, 747
Kalirai, J. S., Hansen, B. M. S., Kelson, D. D., *et al.* 2008, *ApJ*, 676, 594
Marigo, P., Girardi, L., Weiss, A., *et al.* 2004, *A&A*, 423,
Méndez, R. H., Teodorescu, A. M., Schönberner, D., *et al.* 2008, *ApJ*, 681, 325
Vassiliadis, E. & Wood, P. 1994, *ApJS*, 92, 125
Ventimiglia, G., Arnaboldi, M., & Gerhard, O.E. 2011 *A&A*, 528, 24
Villaver, E. & Stanghellini, L. 2005 *ApJ*, 632, 854
Williams, B. F., Ciardullo, R., Durrell, P. R., *et al.* 2007, *ApJ*, 656, 756