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The PN.S ETG survey

M. Arnaboldi[1,2], C. Pulsoni[3], O. Gerhard[3] and PN.S Consortium

[1]European Southern Observatory, K. Schwarzschild str. 2, 85748 Garching, Germany
email: `marnabol@eso.org`

[2]INAF - Astrophysical Observatory of Turin, Strada Osservatorio 20, 10025, Pino Torinese, Italy

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

Abstract. We have analyzed the velocity fields in the halos of thirty-three early-type galaxies (ETGs) with planetary nebulae (PNs) as tracers, reaching radii of up to $\sim 8R_e$. The sample comprises twenty-five galaxies from the Planetary Nebulae Spectrograph (PN.S) ETG survey and eight further galaxies with extended PN velocity data from the literature and new Counter-Dispersed imaging observations. The catalogues from these thirty-three ETGs provide astrometric positions and heliocentric line-of-sight velocities for a total of 8354 extragalactic PNs. All these catalogues are treated homogeneously for the identification of kinematic outliers and the separation between main galaxy/satellites in each galaxy field-of-view. We discuss the rotation velocities, velocity dispersion profiles and radial trends of the specific angular momentum, separating between slow rotators and fast rotators. We compare the properties of the $V/\sigma(R)$ and $\sigma(R)$ profiles with predictions of 2D velocity fields from hydro-dynamical cosmological simulations. We briefly mention the possible origin of the quasi-Keplerian steeply decreasing profile galaxies which encompasses about one fourth of the current sample.

Keywords. ISM: planetary nebulae: general. Galaxies: elliptical and lenticular, cD; evolution; formation, halos, kinematics and dynamics

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1. Introduction

The outer halos of bright early-type galaxies are important sites for testing the late mass assembly process predicted by the ΛCDM hierarchical model. According to the two-phase formation scenario, an initial fast assembly stage is dominated by dissipative processes and rapid star formation, fueled either by infall of cold gas or by major mergers. It is then followed by minor merger episodes that increase the size of the galaxy halos in an efficient way (Oser *et al.* 2010, Hirschmann *et al.* 2012). The late assembly of the outer halos is imprinted in distinctive signatures of the spatial distributions of the accreted halo stars, and their kinematics. The numerical simulations from Abadi *et al.* (2006) show that while the dark matter particles have a mild radial anisotropy, the orbits of accreted stars are strongly radially biased, with radial anisotropy monotonically increasing with radius. Recent hydro-dynamical simulations of galaxy assembly show that the relative fraction of *in-situ* stars and accreted stars in a galaxy varies with the galaxy mass (Rodriguez-Gomez *et al.* 2016), and that these two components have steeper/shallower radial gradients of their surface brightness profiles (Abadi *et al.* 2006, Pillepich *et al.* 2014). Thus the radial trends of the spatial distribution their substructures are valuable observables that can be used to constrain the accretion histories of galaxies. Furthermore, kinematics observations of halo tracers can be used to constrain the orbital distribution and dynamical mass in the systems.

Probing the spatial distribution of stars and their motions at distances larger than two effective radii (the effective radius, or R_e, is the radius that contains half of the total light) is challenging as the surface brightness of the halos becomes only a few percent of the sky brightness. This is particularly difficult for absorption line measurements, given the required high signal-to-noise ratio for the determination of the high order moments of the line-of-sight velocity distribution (LOSVD) that are sensitive to the stellar orbits (e.g. Gerhard 1993). This is resolved by using stellar probes that overcome the limit of steeply decreasing surface brightness profiles, such as globular clusters (GCs, e.g. Brodie *et al.* 2014) and Planetary Nebulae (PNs).

PNs are the late phases of Sun-like stars in the mass range $8 - 1$ $M_{\odot}$. In old stellar populations like those found in the halos of early-type galaxies, one star every $10^6 - 10^7 L_{\odot}$ is expected to be in such phase (Buzzoni *et al.* 2006). PNs are established probes of their parent stars because their number scales with the total bolometric luminosity of the associated stellar population, via the luminosity specific PN number, or α parameter for short, whereby $N_{PN} = \alpha L_{Bol,gal}$. In normal ETGs, the number of PNs trace the light associated with the stellar component in a galaxy (Coccato *et al.* 2009; Cortesi *et al.* 2013; Coccato 2017, this volume). PNs are easily identified in narrow band imaging surveys (Arnaboldi *et al.* 2002; Longobardi *et al.* 2013), as the nebula surrounding the central core star (a hot white dwarf) is very efficient in re-emitting up to 15% of the UV-continuum in the optical green line of the [OIII] doublet, at 5007Å (Dopita *et al.* 1992). Once the PN candidates are identified, the follow-up spectroscopy provides the line-of-sight velocities (LOSVs) of these individual stars with accuracy down to a few kms^{-1} (Arnaboldi *et al.* 2008, Longobardi *et al.* 2015). The PN LOSVDs as function of radius, the 2D velocity fields and the point-symmetry properties of the velocity fields, as well as the specific angular momentum $\lambda(R)$ profiles, can be measured for stellar halos for a wide range of galaxy luminosities and masses, whereas other kinematic probes (such as globular clusters X-rays and lensing measurements) are biased towards the massive galaxies.

A recent development is that in cD galaxies, at radii larger than 70 kpc, a transition is seen from galaxy to intracluster light, signalled by the measurement of a *PN-scarce* vs. a *PN-rich* outer stellar population (e.g M87, Longobardi *et al.* 2013) and M49, Hartke *et al.* 2017, this volume).

Because the detailed properties of individual stellar halos are the results of a stochastic process (Rodriguez-Gomez *et al.* 2016), information on the accretion is to be looked for in the different spatial and velocity distributions of the discrete tracers. In the case of GCs and PNs, their specific luminosity frequencies depend on total luminosities, absolute magnitudes and morphological types of their galaxy hosts, such that GCs frequencies are largest for the smallest and most massive galaxies, while the PN frequency is largest for L^* galaxies (Coccato *et al.* 2013). A vivid example is provided by the halo of M31, the giant Andromeda galaxy. The map of globular clusters in the M31 halo overlaid on the surface density map of metal poor stars from the PANDAS survey shows that GCs are prominent on streams at very large radii ($R > 50$ kpc) but do not trace the bulk of the light in the brighter inner halo, see Veljianoski *et al.* (2014). This complementarity is reminiscent of spatial segregation that arises in hydro-dynamical simulations, see for example Murante *et al.* (2007) and also recent computations from Amorisco (2017). In these accretion histories, the star particles that come from merging of massive progenitors are found preferentially at smaller radii, while star particles that come into the system from stripping events of low mass progenitors are found at larger radii. Thus different accretion histories (i.e. stochasticity) and progenitors may lead to different observed velocity fields and spatial distribution of tracers for galaxies of the same stellar mass.

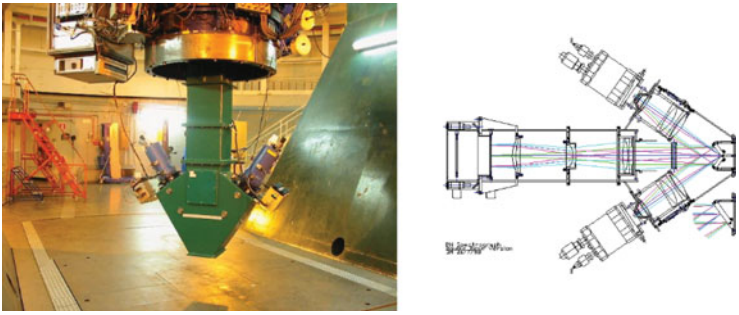

Figure 1. Left: the PN.S mounted at the Cassegrain Focus of the WHT on La Palma Island, Spain. Right: optical layout of the PN.S, indicating the dichroic (left), the narrow band filter (middle) and the concave grating (top right) that splits the pupil image into two - Right and Left - arms.

The purpose of the Planetary Nebulae Spectrograph (PN.S) ETG project is to map the spatial, velocity and angular momentum distribution for stellar halos in ETGs, using PNs as tracers. In what follows we present a short summary of this survey which is now the most extended survey of extragalactic PNs in ETGs to date.

2. The PN.S survey of ETGs

The PN.S ETGs survey is based on data collected with the PN.S mounted at the William Herschel Telescope (WHT) on La Palma, see an image of the PN.S instrument in Fig. 1. The PN.S is a custom built instrument designed for counter dispersed imaging (Douglas *et al.* 2002), that allows the identification of the [OIII] λ 5007 Å monochromatic emission and the measurement of its Doppler shifted observed wavelength in a single observing run. The PN.S works with a pair of images through a single narrow-band filter and dispersed in opposite directions by a concave grating element, as shown by the optical layout in Fig. 1. Despite a slightly lower optical efficiency than direct imaging (because of the use of gratings) the PN.S achieves equally good results because the images can be obtained simultaneously and are thus less influenced by changes in photometric conditions. A PN identification consists of two 3σ events in the same row of both detectors, and there is more signal redundancy in a pair of matching peaks than in a single peak of the same significance. All the observing time spent on the galaxy field-of-view contributes both to the identification of PNs in a given galaxy field and to the spectroscopy to measure the Doppler shift of the [OIII] λ 5007 Å emission.

The goal of the PN.S ETG survey (P.I. Magda Arnaboldi) is to measure the kinematics, dynamics, angular momentum, and mass in ETG halos in the nearby Universe, within a distance of $D \leqslant 25$ Mpc. The range of structural parameters, such as luminosity, central velocity dispersion, ellipticity and isophotes shapes are shown in Fig. 2. Twenty-five ETGs were observed with the PN.S; additional two galaxies were observed with new Counter Dispersed Imaging (CDI) with FORS2@VLT, and six PN catalogs were collected from the literature. All catalogs were uniformly validated for completeness, removal of background galaxy emissions and kinematical outliers (Arnaboldi *et al.* in prep.). The catalogs were then processed to identify the contribution from nearby satellites using the probability membership method from McNeil-Moylan *et al.* (2012). In summary, we were able to measure astrometry and LOSVs for nearly 80 to 700 PNs in each sample galaxy, typically covering radii out to 5 to 8 R_e, giving a total detected sample of 8354 extragalactic PNs.

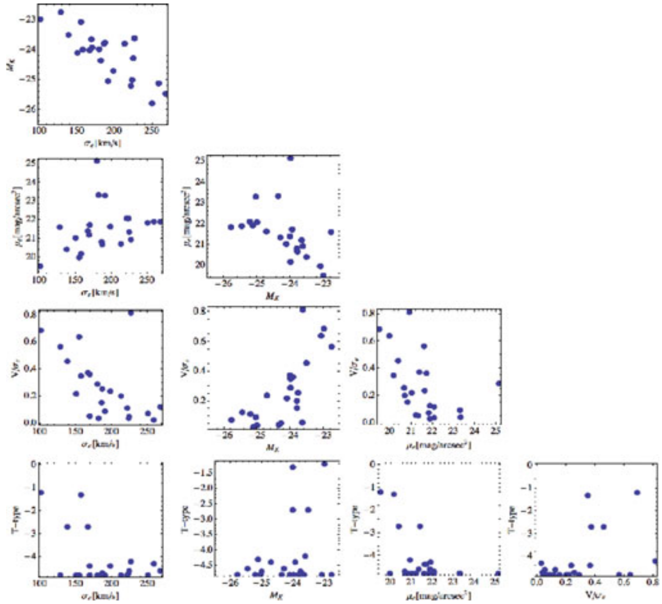

Figure 2. Structural parameters, i.e. luminosity, central velocity dispersion, ellipticity and isophote shapes, for the magnitude limited sample of galaxies covered by the PN.S ETG survey.

In Pulsoni *et al.*, in prep., we obtained the extended velocity fields and assessed the symmetry properties of the LOSVDs in the outer halos. A few galaxies for which the most radially extended and statistical significant samples are available show 2D velocity fields that are not point-symmetric, e.g. NGC 5128. Such properties indicate that the stellar kinematics in the outer regions are out of dynamical equilibrium, because of recent merger events. When the 2D velocity field is compatible with point symmetry, the PN catalog can be folded, thus doubling the number of tracers. The smoothed 2D maps of the first (i.e. average velocity $v(R)$) and second moment (i.e. velocity dispersion $\sigma(R)$) of the LOSVD are then compared with the simulated maps of $v/\sigma(R)$ and $\sigma(R)$ out to $5R_e$ for ETGs from Wu *et al.* (2014). We briefly summarize the results of the comparison in turn.

- The measured halo v/σ at $5R_e$ for the ETGs in the PN.S survey correlate with those within one R_e for most of the sample galaxies. Thus the division between slow and fast rotators in the outer halos is similar as in the cores, as measured by the ATLAS^{3D} project (Cappellari *et al.* 2011). There are some more complicated cases though, where single galaxies cross the separating line in specific angular momentum λ_R (Emsellem *et al.* 2007), as we go from the cores to the outer halos (Pulsoni *et al.* 2017).
- The $\sigma(R)/\sigma(R_e)$ vs. R/R_e profiles for the ETGs in the PN.S survey show quasi-Keplerian steeply falling profiles for about one fourth of the galaxies in the sample. Interestingly these profiles are not measured for the simulated halos of ETGs in Wu *et al.* (2014). The open questions about the nature of quasi-Keplerian ETGs are: are they face-on disks of fast rotators? Is the quasi-Keplerian behavior signaling low-mass halos or strong radial anisotropy? As shown by de Lorenzi *et al.* (2008), de Lorenzi *et al.* (2009) and Morganti *et al.* (2013), quasi-Keplerian profiles are compatible with ΛCDM dark matter halos, and a range of dark matter fractions and anisotropy profiles. For galaxies with decreasing $\sigma(R)$ profiles, there is a strong degeneracy in dynamical models for the mass determination. Current work is in progress for a Jeans-Kurtosis analysis of the spherical ETGs (Napolitano *et al.* 2017, in prep.).

3. Summary

In this contribution we briefly covered the following observational results:

- GCs and PNe trace a complementary mix of progenitor systems.
- Outer halos are dynamically young structures. Some may even be out of equilibrium and violate point symmetry.
- Angular momentum in the halo and within one R_e are correlated, but some transition cases exist, which cross the fast-rotator/slow-rotator division.
- Halo orbits are mildly to strongly radially biased. This may be a record of radial infall orbits.
- Velocity-dispersion dichotomy: what is the nature of the quasi- Keplerian ETGs?

Future projects for PN studies include using PN tracers for measuring Oxygen abundance, PNLF morphologies and their relations to parent stellar populations, in addition to the kinematical mapping of the outer halos.

4. Acknowledgments

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