The halo of M 105 and its group environment as traced by planetary nebula populations II. Using kinematics of single stars to unveil the presence of intragroup light around the Leo I galaxies NGC 3384 and M 105


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The halo of M 105 and its group environment as traced by planetary nebula populations

II. Using kinematics of single stars to unveil the presence of intragroup light around the Leo I galaxies NGC 3384 and M 105*

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ABSTRACT

Context. M 105 (NGC 3379) is an early-type galaxy in the nearby Leo I group, the closest galaxy group to contain all galaxy types and therefore an excellent environment to explore the low-mass end of intra-group light (IGL) assembly.

Aims. We present a new and extended kinematic survey of planetary nebulae (PNe) in M 105 and the surrounding 30' × 30' in the Leo I group with the Planetary Nebula Spectrograph (PN.S) to investigate kinematically distinct populations of PNe in the halo and the surrounding IGL.

Methods. We use PNe as kinematic tracers of the diffuse stellar light in the halo and IGL, and employ photo-kinematic Gaussian mixture models to (i) separate contributions from the companion galaxy NGC 3384, and (ii) associate PNe with structurally defined halo and IGL components around M 105.

Results. We present a catalogue of 314 PNe in the surveyed area and firmly associate 93 of these with the companion galaxy NGC 3384 and 169 with M 105. The PNe in M 105 are further associated with its halo (138) and the surrounding exponential envelope (31). We also construct smooth velocity and velocity dispersion fields and calculate projected rotation, velocity dispersion, and $I_\phi$ profiles for the different components. PNe associated with the halo exhibit declining velocity dispersion and rotation profiles as a function of radius, while the velocity dispersion and rotation of the exponential envelope increase notably at large radii. The rotation axes of these different components are strongly misaligned.

Conclusions. Based on the kinematic profiles, we identify three regimes with distinct kinematics that are also linked to distinct stellar population properties: (i) the rotating core at the centre of the galaxy (within 1$R_\text{eff}$) formed in situ and is dominated by metal-rich ([M/H] > 0) stars that also likely formed in situ, (ii) the halo from 1 to 7$R_\text{eff}$ consisting of a mixture of intermediate-metallicity and metal-rich stars ([M/H] > −1), either formed in situ or was brought in via major mergers, and (iii) the exponential envelope reaching beyond our farthest data point at 16$R_\text{eff}$, predominately composed of metal-poor ([M/H] < −1) stars. The high velocity dispersion and moderate rotation of the latter are consistent with those measured for the dwarf satellite galaxies in the Leo I group, indicating that this exponential envelope traces the transition to the IGL.

Key words. galaxies: individual: M 105 – galaxies: elliptical and lenticular, cD – galaxies: groups: individual: Leo I – galaxies: halos – planetary nebulae: general

1. Introduction

The galaxy M 105 (NGC 3379) of the Leo I group prominently featured in a lively debate over the dark matter (DM) content and its spatial distribution in massive early-type galaxies (ETGs; Romanowsky et al. 2003; Dekel et al. 2005; de Lorenzi et al. 2009; Napolitano et al. 2009; Morganti et al. 2013). Using data obtained with the Planetary Nebula Spectrograph (PN.S), Romanowsky et al. (2003) and Douglas et al. (2007) found that several intermediate-luminosity elliptical galaxies – M 105 among them – appeared to have low mass and low-concentration DM halos, if any, based on their rapidly falling velocity dispersion profiles. This is in contrast with inferences made for the massive dark halos of giant elliptical galaxies (e.g., Awaki et al. 1994; Kronawitter et al. 1999; Humphrey et al. 2012), and weak and strong gravitational lensing (e.g., Hoekstra et al. 2004; Mandelbaum et al. 2006; Wilson et al. 2001; Koopmans et al. 2006; Tortora et al. 2010, 2014). Follow-up studies discussed whether the apparent lack of DM in the halo of M 105 was linked to the gravitational potential-orbital anisotropy degeneracy and viewing-angle effects (Dekel et al. 2005; Douglas et al. 2007; de Lorenzi et al. 2009; Weijmans et al. 2009; Morganti et al. 2013). Furthermore, the strong decrease in the line-of-sight (LOS) velocity dispersion may not continue in the outer halo: Pulsoni et al. (2018) identified several ETGs where the decline in the LOS velocity dispersion was followed by an increase in the outer halo (e.g., NGC 1023, NGC 2974, NGC 4374, NGC 4472). As the measurements of Romanowsky et al. (2003) were confined within eight effective radii (i.e. within the field of view of a single PN.S pointing and assuming an effective radius of $R_{\text{eff,M 105}} = 54''8$, Capaccioli et al. 1990), they may have missed a kinematic transition at larger radii.

Using new, extended imaging and kinematic samples of planetary nebulae (PNe), we aim to investigate whether the LOS properties: (i) the rotating core at the centre of the galaxy (within 1$R_\text{eff}$) and (ii) the halo from 1 to 7$R_\text{eff}$.
velocity dispersion profile decline in M 105 continues in the outer halo or whether a change in kinematics is observed. Our work builds on the first paper in this series, in which Hartke et al. (2020, hereafter H+2020), presented a wide-field photometric survey of PN candidates in M 105 and the surrounding 0.5 × 0.5 deg⁻². H+2020 found a variation of the luminosity-specific PN number α (as defined in Sect. 3.4) with radius in the halo of M 105, with the α-parameter being seven times higher in the extended halo than in the inner halo. These authors inferred that the PN population with a high α-parameter is linked to a diffuse population of metal-poor stars ([M/H] ≤ −1.0, Lee & Jang 2016), whose light distribution is governed by an exponential surface brightness (SB) profile. The light distribution in the inner halo is dominated by intermediate-metallicity and metal-rich stars ([M/H] > −1.0, Lee & Jang 2016) following a Sérsic SB profile and a low-α-parameter population of PNe. In this paper, which is the second of the series, we wish to investigate whether the two PN populations that H+2020 identified also possess distinct kinematic signatures and which constraints these would place on the assembly history of M 105 and its group environment, the Leo I group.

The Leo I group is the closest group that contains all (i.e. early and late) galaxy types (de Vaucouleurs 1975). The eleven brightest and most massive member galaxies can be further divided into two subgroups. Four are associated with the so-called Leo Triplet. The remaining seven, among them M 105 and NGC 3384, which are the main subjects of this paper, are associated with the M 96 (NGC 3368) group. In addition to these bright member galaxies, dwarf galaxies make up the largest number of group members: Müller et al. (2018) compiled the most recent catalogue of dwarf galaxies in the group, adding 36 new candidates to the previously known 52 dwarf galaxies.

With its low mass and proximity, the Leo I group is an excellent environment in which to explore the low-mass end of intra-group light (IGL) assembly. Based on deep and wide-field photometry, Watkins et al. (2014) attributed at most a few per cent of the light in their survey footprint to the IGL. Assuming that all PNe associated with the exponential SB profile trace the IGL, H+2020 determine the fraction of PNe associated with the IGL to be 22%, while the fraction in terms of stellar SB is 3.8%. This low IGL fraction seemingly contradicts results from numerical simulations, which predict IGL fractions of between 12% and 45% (Sommer-Larsen 2006; Rudick et al. 2006). However, it is unclear whether this mismatch is a resolution effect or whether a dimmer IGL is expected in lower mass groups compared to more massive environments such as galaxy clusters (Purcell et al. 2007; Watkins et al. 2014). Evaluating the dynamical status of the PNe populations at large radii is imperative for constraining the IGL properties in the Leo I group.

This paper is organised as follows: in Sect. 2, we describe the data from photometric and slitless spectroscopic surveys in the Leo I group and the compilation of the final cross-matched data catalogues. Section 3 describes the decomposition of the sample into PNe associated with NGC 3384 and M 105 based on photo-kinematic models. We describe the kinematics of PNe in the halo and envelope of M 105 in Sect. 4. We discuss our results in Sect. 5 and put them into the context of the Leo I group at large. We summarise and conclude our findings in Sect. 6.

In this paper, we adopt a physical distance of 10.23 Mpc to M 105. The corresponding physical scale is 49.6 pc/″. This tip of the red giant branch (TRGB) distance was independently determined by Harris et al. (2007a,b) and Lee & Jang (2016) and agrees well with that determined from the bright cut-off of the planetary nebula luminosity function (PNLF) determined by H+2020 as well as with that derived from SB fluctuation measurements (SBF; Tonry et al. 2001). The effective radius of M 105 derived from broad-band photometry is $R_{\text{eff,M 105}} = 54''8 \pm 3''5$ (Capaccioli et al. 1990), corresponding to a physical scale of 2.7 kpc.

2. The data

2.1. Photometric survey

H+2020 presented the Subaru Surprime-Cam survey for PNe candidates in the Leo I group. Here, we only briefly summarise the survey objectives, data reduction, and PN candidate identification and validation. H+2020 identified PN candidates from the combined use of narrow- [O III] ($\lambda_{\text{cen}} = 5500$ Å) and broadband V-band ($\lambda_{\text{off}} = 5029$ Å) images. Using CMD-based automated detection techniques (Arnaboldi et al. 2002, 2003), these authors identified 226 PNe candidates within a limiting magnitude of $m_{5007, \text{lim}} = 28.1$. These candidates are denoted by grey crosses in the right panel of Fig. 1. The photometric survey thus covers 2.6 magnitudes from the bright cut-off of the PNLF at $m_{5007} = 25.5$. The unmasked survey area (excluding image artefacts and regions with a high background value) covered 0.2365 deg² on the sky, which corresponds to 67.7 kpc along the major axis of M 105. The survey also covers the halos of NGC 3384 and NGC 3389. The survey footprint is outlined by the grey dashed rectangle in the left panel of Fig. 1. The 214 PNe are indicated with cyan circles in the right panel of Fig. 1. These data were used to independently validate the photometric sample in H+2020. In 2019, M 105-W was observed again, along with the fields M 105-SW (blue rectangle) and M 105-N (purple rectangle). The total exposure times per field are given in Table 1, NGC 3384 was first observed as part of the PN.S survey of S0 galaxy kinematics (Courtesi et al. 2013a). In total, 101 PNe were observed; these are shown with green diamonds in the right panel of Fig. 1. The availability of these data will enable an improved photo-kinematic decomposition of the PN sample (see Sect. 3).

2.2. The extremely extended PN.S ETG survey in M 105 and NGC 3384

The extremely extended PN.S ETG ($\epsilon^2$PN.S) survey includes data from the ePN.S survey (Arnaboldi et al. 2017; Pulsoni et al. 2018), namely two fields centred on M 105 and NGC 3384 respectively. The first PN.S observations of M 105 were part of the PN.S ETG survey (Douglas et al. 2007). The resulting 214 PNe are indicated with cyan circles in the right panel of Fig. 1 and in the left panel, where the field is outlined in the same colour and denoted M 105-C. In 2017, we observed two additional fields (M 105-W and M 105-S). These were identified by brown and red rectangles in the left panel of Fig. 1. These data were used to independently validate the photometric sample in H+2020. In 2019, M 105-W was observed again, along with the fields M 105-SW (blue rectangle) and M 105-N (purple rectangle). The total exposure times per field are given in Table 1, NGC 3384 was first observed as part of the PN.S survey of S0 galaxy kinematics (Courtesi et al. 2013a). In total, 101 PNe were observed; these are shown with green diamonds in the right panel of Fig. 1. The availability of these data will enable an improved photo-kinematic decomposition of the PN sample (see Sect. 3).

2.2.1. Field-to-field variation and catalogue matching within the $\epsilon^2$PN.S survey

The PN.S pipeline processes the survey data field by field. We therefore had to cross-match the individual catalogues to create a homogeneous master catalogue encompassing data from the six fields. We used an iterative coordinate-matching algorithm with a matching radius of 5″. We chose this seemingly large radius due to the positional uncertainties on the PN.S data. As already stated in H+2020, we identify the 30 PNe with measurements in
Fig. 1. DSS image of the Leo I group with a scale-bar in the lower-right corner indicating a physical scale of 10 kpc. North is up, east to the left. Left: rectangles show the field outlines of the Surprime-Cam photometry survey (grey dashed outline), individual fields of the e2PN.S survey (solid outlines), and the HST fields analysed by Lee & Jang (2016, hashed rectangles). Right: overplotted are the PN candidates detected with Surprime-Cam (Hartke et al. 2020, grey plus symbols). The data from the e2PN.S survey (Pulsoni et al. 2018) for NGC 3384 (first published by Cortesi et al. 2013a) and M 105 (first published by Douglas et al. 2007) are indicated by cyan and green points and diamonds respectively. Squares denote the PNe from the e2PN.S survey already presented in (H+2020) and bold crosses newly detected PNe from this work. The colours of the symbols correspond to those of the field outlines in the left panel.

Table 1. Summary of the PN.S observations used in this paper.

<table>
<thead>
<tr>
<th>Field name</th>
<th>RA [hh:mm:ss]</th>
<th>Dec [dd:mm:ss]</th>
<th>Exposure time [h]</th>
<th>Year</th>
<th>NPN (a)</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>M 105-S</td>
<td>10:47:49.59</td>
<td>+12:25:53.8</td>
<td>3.5</td>
<td>2017</td>
<td>18</td>
<td></td>
</tr>
<tr>
<td>M 105-SW</td>
<td>10:47:14.40</td>
<td>+12:28:30.0</td>
<td>4.0</td>
<td>2019</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td>M 105-N</td>
<td>10:47:42.39</td>
<td>+12:43:53.8</td>
<td>4.0</td>
<td>2019</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>M 105-C</td>
<td>10:47:49.60</td>
<td>+12:36:54.0</td>
<td>18.8 (b)</td>
<td>2002, 2003</td>
<td>217</td>
<td>(1)</td>
</tr>
</tbody>
</table>

Notes. The top part of the table refers to new observations, while the bottom part summarises data from published catalogues. (a) The number of PNe NPN refers to the 3σ-clipped catalogue. The sum of NPN presented in this table is larger than the total number of PNe in the main text as some PNe are observed in two fields. (b) This exposure time is considerably longer compared to the other fields, but was obtained under a variety of seeing conditions. Had they been taken in nominal 1′′ seeing conditions, the equivalent would be 7 hours (see Douglas et al. 2007, for details).

References. (1) Douglas et al. (2007); (2) Cortesi et al. (2013a).

We also identified 5 PNe in the western field based on 2017 data alone (H+2020) and in the deeper stack, including the data from 2019. These are denoted with orange squares in Fig. 2. They all scatter about the one-to-one line, and the scatter is within the velocity error of the PN.S. We conclude that there is no velocity offset between the observations taken in 2017 and 2019.

2.2.2. Photometric calibration and catalogue matching with Surprime-Cam photometry

We matched the kinematic catalogue compiled in the previous section with the photometric one from H+2020. Like H+2020, we used a matching radius of 5′′ due to the relatively large positional uncertainty on the PN.S data. We used this matched sample to determine the zero-point magnitude of each of the newly identified PNe.
observed PN.S fields. Figure 3 shows a comparison of the $AB$ magnitudes obtained with the PN.S after applying the zero-point offset with those from Surprime-Cam. The colour-coding is the same as in Fig. 1.

The large scatter about the one-to-one line is not surprising, as the PN.S had not been optimised to obtain accurate photometry. While the photometric accuracy is acceptable in nearby galaxies (e.g., Merrett et al. 2006), Hartke et al. (2018) found a similarly large scatter of PN.S magnitudes compared to accurate Surprime-Cam ones in the Virgo galaxy M49. In order to convert the $AB$ magnitudes to $m_{5007}$, we used the relation determined by Arnaboldi et al. (2003): $m_{5007} = m_{AB} + 2.49$.

To gauge the depth of the $e^{2}$PN.S survey, we constructed the PNLF of each of the fields. Figure 4 shows the PNLF for each field with the same colour coding as in Fig. 1. The black histogram denotes the PNLF of all $e^{2}$PN.S PNe. For comparison, we also show the PNLF based on the Surprime-Cam photometry in grey. We only included data brighter than the limiting magnitude $m_{5007, \text{lim}} = 28.1$. The vertical dotted lines denote the PNLF bright cut-offs corresponding to the distances to M 105 (black, $m_{5007, M105} = 25.54$) and NGC 3384 (grey, $m_{5007, N3384} = 25.76$) respectively. Except for one over-luminous object, all PNe are fainter than the bright cut-off $m_{5007, M105}$.

The deepest fields are centred on M 105 and NGC 3384, with the faintest object nearly reaching 30th magnitude. However, the $e^{2}$PN.S survey is likely only complete to a limiting magnitude $m_{5007, \text{lim}} = 27.5$. This is the magnitude at which the number of PNe starts to decrease as a function of magnitude, contrary to the exponential increase that is theoretically expected (see also H+2020).

2.2.3. Excluding velocity outliers

To remove velocity outliers that may be sources of contamination, we first calculated the mean velocity and velocity dispersion $\sigma$ of the whole sample – including PNe associated with M 105 and NGC 3384 – using a robust fitting technique (McNeil et al. 2010). The left panel of Fig. 5 shows the phase-space of PN candidates in the $e^{2}$PN.S footprint with the $x$-coordinate along the major axis of M 105. The right panel of Fig. 5 shows the corresponding LOS velocity distribution (LOSVD) with the 1, 2, and 3$\sigma$ intervals shaded in blue. The velocity range covered by the different filter configurations is $-400 < v \leq 2400 \text{ km s}^{-1}$. We clipped four PNe with velocities outside the velocity range of $\pm 3\sigma$ about the robust mean. Table 1 contains the final $e^{2}$PN.S catalogue after combining observations from multiple fields, correcting the magnitude zero-point, and 3$\sigma$-clipping. In summary, the final catalogue provided in Table A.2 contains coordinates, velocities, and magnitudes for 319 PNe.
2.2.4. Completeness and sources of contamination

The completeness of the photometric catalogue was extensively discussed in H+2020. Due to the nature of the PNS instrument, we can immediately discard objects with a continuum, as the continuum appears as a stripe in slitless spectroscopy. This requirement excludes the majority of Ly-α emitters with a continuum redder than the [O III]5007 Å emission line. Background [O II] emitters at z ~ 0.34 can be discarded as the spectral resolution of the PNS is sufficient to resolve both emissions from the redshifted [O II] 3727 Å doublet. However, we cannot use the second bluer line of the [O III] doublet commonly used to distinguish PNe from contaminants as it is not covered by the PNS bandpass. We therefore resorted to statistical methods to estimate the contamination from Ly-α galaxies without a measurable continuum, assuming that the number of background galaxies is uniformly distributed in a velocity histogram (Spiniello et al. 2018).

Based on the presence of three objects in the velocity range 1400 < v ≤ 2400 km s⁻¹ and one in the velocity range ~400 < v ≤ 400 km s⁻¹ (see Fig. 5), which are likely not PNe, we expect 7 objects such as background galaxies in the full velocity range, corresponding to a fraction of 2.2%. The result is very similar to that estimated by H+2020 (2.6%) based on a subset of the data and the estimate of Spiniello et al. (2018, ~2%) for slitless spectroscopy of PNe in the Fornax cluster.

3. Galaxy membership assignment based on photo-kinematic models

In order to decompose the kinematic PN sample into subcomponents associated with M 105 and NGC 3384, we modelled the observed PN in position–velocity space using a luminosity-weighted multi-Gaussian model. The luminosity weights are pre-determined from broad-band photometry, while the kinematic parameters are free parameters of the Gaussian-mixture model. Gaussian-mixture models are widespread in the astronomical literature to disentangle multi-component LOSVDs (see e.g., Walker & Peñarrubia 2011; Amorisco & Evans 2012; Watkins et al. 2013; Agnello et al. 2014; Hartke et al. 2018; Longobardi et al. 2018a). In the following simple modelling, we assume that there is no strong ongoing interaction between the two galaxies. This assumption is supported by the absence of strong tidal features or bridges of stars connecting the two galaxies (Watkins et al. 2014).

3.1. Disk–bulge decomposition of NGC 3384

To model the kinematics of NGC 3384, we use the disk-bulge decomposition method developed by Cortesi et al. (2011) and subsequently applied to the PNS survey of 50 galaxy kinematics (Cortesi et al. 2013b), including the decomposition of NGC 3384 into its disk and bulge components.

The LOS velocity of the disk as function of azimuthal angle $\phi_{3384}$ and radius $r_{3384}$ measured with respect to the centre of NGC 3384 can be expressed as

$$v_{\text{LOS}}(r_{3384}, \phi_{3384}; v_{\text{rot}}, \sigma_{\text{rot}}, \sigma_{\text{sys}}) = v_{\text{sys};3384} + v_{\text{rot}} \sin(i) \cos(\phi_{3384}),$$

where $v_{\text{rot}}$ is the mean rotation velocity of the galaxy and i the inclination at which the disk is observed. The corresponding velocity dispersion is

$$\sigma_{\text{LOS}}^2(r_{3384}, \phi_{3384}; v_{\text{rot}}, \sigma_{\text{rot}}, \sigma_{\phi}) = \sigma_{\text{rot}}^2 \sin^2(i) \sin^2(\phi_{3384}) + \sigma_{\phi}^2 \sin^2(i) \cos^2(\phi_{3384}) + \sigma_{i}^2 \cos^2(i),$$

where $\sigma_{\text{rot}}$, $\sigma_{\phi}$, and $\sigma_{i}$ are its components in cylindrical coordinates. In edge-on galaxies, the contribution along the z-axis is small. Hence, in the following term $\sigma_{\text{rot}}^2 \cos^2(i)$ can be dropped. Assuming a Gaussian LOSVD, the disk kinematics can be described as

$$v_{\text{N3384, disk}}(v_k, r_{3384}, \phi_{3384}; v_{\text{rot}}, \sigma_{\text{rot}}, \sigma_{\phi}) = \frac{1}{\sqrt{2\pi}\sigma_{\text{LOS}}} \exp\left(-\frac{(v_k - v_{\text{LOS}})^2}{2\sigma_{\text{LOS}}^2}\right).$$

The contribution from the bulge is described as a Gaussian centred on the systemic velocity of NGC 3384 with velocity dispersion $\sigma_{\text{N3384, bulge}}$, assuming it does not rotate significantly:

$$v_{\text{bulge}}(v_k, r_{3384}, \phi_{3384}; \sigma_{\text{N3384, bulge}}) = \frac{1}{\sqrt{2\pi}\sigma_{\text{N3384, bulge}}} \exp\left(-\frac{(v_k - v_{\text{sys},3384})^2}{2\sigma_{\text{N3384, bulge}}^2}\right).$$
The two kinematic components of the LOSVD are weighted by the SB profiles as described in Sect. 3.3. In order to account for the variation of the LOSVD as a function of radius, we evaluate it in five concentric ellipsoidal bins with the same geometry as the galaxy’s isophotes centred on NGC 3384. Therefore, the parameters $v_{\text{rot}}, \sigma_r, \sigma_\phi$, and $\sigma_{\text{M105,Exp}}$ are evaluated independently in each of the five bins. Following Cortesi et al. (2011, 2013b), we can reduce the parameter space using the epicycle approximation that holds for disk galaxies with approximately flat rotation curves (see, e.g., Binney & Tremaine 1987) and links the radial velocity dispersion with the tangential one: $\sigma_\phi = \sigma_r / \sqrt{2}$.

3.2. Kinematic model of M 105

Following the discovery of a PN population associated with an exponential SB profile in addition to the Sérsic halo (H+2020), we model M 105’s kinematics LOSVD with two Gaussians; both centred on the galaxy’s systemic velocity $v_{\text{sys,M105}}$. They differ in their velocity dispersions, which we denote with $\sigma_{\text{M105,ser}}$ and $\sigma_{\text{M105,Exp}}$, respectively:

$$V_{\text{M105,ser}}(r, r_{\text{M105,ser}}; \sigma_{\text{M105,ser}}) = \frac{1}{\sqrt{2\pi}\sigma_{\text{M105,ser}}} \exp\left(-\frac{(v - v_{\text{sys,M105}})^2}{2\sigma_{\text{M105,ser}}^2}\right).$$

(5)

$$V_{\text{M105,Exp}}(r, r_{\text{M105,Exp}}; \sigma_{\text{M105,Exp}}) = \frac{1}{\sqrt{2\pi}\sigma_{\text{M105,Exp}}} \exp\left(-\frac{(v - v_{\text{sys,M105}})^2}{2\sigma_{\text{M105,Exp}}^2}\right).$$

(6)

Again, in order to account for any variation of the LOSVD with radius, the parameters $\sigma_{\text{M105,ser}}$ and $\sigma_{\text{M105,Exp}}$ are evaluated in five concentric elliptical annuli with the same geometry as the galaxy’s isophotes, but this time centred on M 105. We assume that the LOS velocity dispersion of the exponentially distributed PN population is larger than that of the one following a Sérsic profile in each bin.

3.3. Constraints on galaxy membership from broad-band photometry and RGB star number counts

As the number density distribution of PNe is closely linked to the stellar light distribution, i.e. the galaxies’ SB profiles (see e.g., Coccato et al. 2009, and Fig. 7), we can obtain further constraints on which PN belongs to which galaxy component from broad-band photometry. The SB profiles of M 105 and NGC 3384 are described by a combination of Sérsic profiles (Sérsic 1963). The intensity $I$ as a function of radius $R$ is:

$$I_{\text{ser}}(R) = I_{\text{eff}} \exp\left(-b_n \left(\frac{R}{R_{\text{eff}}}\right)^{1/n} - 1\right),$$

(7)

with

$$b_n = 2n - \frac{1}{3} + \frac{0.099876}{n}.$$  

(8)

The effective intensity $I_{\text{eff}}$ is measured at the effective radius $R_{\text{eff}}$ at which half the luminosity is enclosed, and the steepness of the profile is controlled by the Sérsic index $n$. The corresponding SB profile is:

$$\mu_{\text{ser}}(R) = \mu_{\text{eff}} + \frac{2.5b_n}{\ln 10} \left(\frac{R}{R_{\text{eff}}}\right)^{1/n} - 1.$$  

(9)

The scale length $h$ and central SB $\mu_0$ are related to the Sérsic quantities as follows:

$$R_{\text{eff}} = 1.678 \cdot h,$$

$$\mu_{\text{eff}} = \mu_0 + 1.826 \left(\frac{R}{h}\right).$$

(10)

In the following, we describe the structural parameters of NGC 3384 and M 105 that were derived in previous works. Table 2 provides a summary in terms of Sérsic structural parameters, and Fig. 6 shows the resulting SB maps for the two galaxies separately, as well as a composite SB map.

3.3.1. NGC 3384

Cortesi et al. (2013b) analysed 2MASS $K$-band images (Skrutskie et al. 2006) with GALFIT (Peng et al. 2010) for the disk–bulge decomposition of NGC 3384. These authors found that the light distribution of the bulge in the $K$-band is best described by a Sérsic profile with effective SB $\mu_{\text{eff,bulge}} = 15.9$, Sérsic index $n = 4$, effective radius $R_{\text{eff,bulge}} = 15''2$, ellipticity $\epsilon_{\text{bulge}} = 0.17$, and position angle $\text{PA}_{\text{bulge}} = 60^\circ51^\prime$.

The light distribution of the disk is described with an exponential profile with central SBs $\mu_0_{\text{disk}} = 18.25$, scale length $h_{\text{3384,disk}} = 63''73$, ellipticity $\epsilon_{\text{3384,disk}} = 0.66$, inclination $i = 70^\circ$, and PA $= 52^\circ5$. H+2020 determined a colour correction of $B - K = -3.75$ for the profiles derived from the 2MASS data by Cortesi et al. (2013b). The left panel of Fig. 7 shows the total $B$-band SB profile of NGC 3384 (grey line) and the contributions from the galaxy disk (blue dashed line) and bulge (red dotted line).
3.3.2. M 105

The light distribution of M 105 was first analytically described by de Vaucouleurs (1948), and is still regarded as one of the cornerstones of the de Vaucouleurs law today. Combining number density profiles of resolved red giant branch (RGB) stellar populations (Lee & Jang 2016) with deep wide-field imaging (Watkins et al. 2014), and their wide-field photometric survey for PNe, H+2020 established a two-component model for the SB profile of M 105. The light distribution in the inner halo is dominated by metal-rich stars following a Sérsic profile with $n_{\text{Ser}} = 2.75$, $R_{\text{eff, Ser}} = 57''$, and $\mu_{\text{eff, Ser}} = 21.73$, denoted by the dotted orange line in the right panel of Fig. 7. The fractional contribution from metal-poor stars increases in the outer halo. Their light distribution is modelled with an exponential profile with $h_0^{\text{Exp}} = 358''$ and $\mu_0^{\text{Exp}} = 27.7$. Watkins et al. (2014) derived a constant ellipticity of $\epsilon_{\text{M,105}} = 0.111 \pm 0.005$ and a position angle of $PA = 70^\circ \pm 1^\circ$ in the outer halo of M 105.

3.4. PN-specific frequency dependency on stellar population parameters

As the number of PNe has been shown to systematically vary with the colour of the parent stellar population (Buzzoni et al. 2006; Longobardi et al. 2015; Hartke et al. 2017), such dependency must be taken into account when using SB profiles derived from integrated starlight as weights for the kinematic model. The connection between a PN population and the underlying stellar population is given by the luminosity-specific PN number, referred to here as the $\alpha$-parameter, which relates the total number of PNe $N_{\text{PN}}$ to the total bolometric luminosity $L_{\text{bol}}$ of the parent stellar population:

$$N_{\text{PN}} = \alpha L_{\text{bol}}.$$  \hfill (12)

For the bolometric correction, we use that derived from theoretical template galaxy models as a function of galaxy colour (Buzzoni 2005; Buzzoni et al. 2006). In the following, we refer to $\alpha_{2.5}$ values, which are calculated in the magnitude interval $m' < m_{5000} < m' + 2.5$. The observed PN number densities for NGC 3384 and M 105 are indicated with green error bars in the left and right panels of Fig. 7, respectively.

For NGC 3384, we assume that the $\alpha$-parameters for disk and bulge are equal (because incompleteness in the centre of the galaxy means we cannot calculate $\alpha_{\text{bulge}}$ separately) and determined $\alpha_{\text{N3384}} = (1.41 \pm 0.15) \times 10^8 \text{PN L}_{\text{bol}}^{-1}$. We only considered PNe that lie within the green 50% contour shown in the right panel of Fig. 6. The resulting best-fit PN number density profile is indicated by the green dash-dotted line in the left panel of Fig. 7.

For M 105, H+2020 determined $\alpha$-parameters for PNe associated with the Sérsic and exponential SB profiles and found $\alpha_{\text{M,105,Ser}} = (1.00 \pm 0.11) \times 10^8 \text{PN L}_{\text{bol}}^{-1}$ and $\alpha_{\text{M,105,Exp}} = (7.10 \pm 1.87) \times 10^8 \text{PN L}_{\text{bol}}^{-1}$. The resulting best-fit PN number density profile is indicated by the green dash-dotted line in the right panel of Fig. 7. As the bulk of the light in M 105 is contributed by metal-rich stars following the Sérsic profile, we use $\alpha_{\text{M,105,Ser}}$ as the denominator of the normalisation. We therefore include the parameters $\alpha_{\text{N3384}} = \alpha_{\text{N3384}}/\alpha_{\text{M,105,Ser}}$ and $\alpha_{\text{M,105,Exp}} = \alpha_{\text{M,105,Exp}}/\alpha_{\text{M,105,Ser}}$ which characterise the variation of $\alpha$ in the bulge and disk components of NGC 3384, as well as in the outer halo of M 105 with respect to the $\alpha$-parameter of the main halo of M 105.

3.5. Bayesian likelihood

The likelihood of a PN $k$ with observed position RA, Dec and velocity $v_k \pm \delta v_k$ can be expressed in terms of the velocity and surface-brightness distributions that we define in the previous three sections. The model component weights are defined as follows:

$$w_{\text{N3384,bulge}} = \frac{\alpha_{\text{N3384,bulge}}}{n_{\text{tot}}},$$  \hfill (13a)

$$w_{\text{N3384,disk}} = \frac{\alpha_{\text{N3384,disk}}}{n_{\text{tot}}},$$  \hfill (13b)

$$w_{\text{M,105,Ser}} = \frac{\Sigma_{\text{M,105,Ser}}}{n_{\text{tot}}},$$  \hfill (13c)

$$w_{\text{M,105,Exp}} = \frac{\Delta_{\text{M,105,Exp}}}{n_{\text{tot}}},$$  \hfill (13d)

where both the $\alpha$-parameters and the surface-brightness profiles $\Sigma$ are completely determined by the broad- and narrow-band photometry as described in Sects. 3.3 and 3.4. The weights are
normalised by

\[ n_{\text{tot}} = \bar{\alpha}_{\text{N3384}, \text{bulge}} + \Sigma_{\text{N3384}, \text{disk}} + \bar{\sigma}_{\text{M105}, \text{Ser}} + \delta \sigma_{\text{M105}, \text{Exp}} + \Sigma_{\text{M105}, \text{Exp}} \]

The corresponding likelihood for a PN \( k \) at its position in phase-space is

\[ L_k = w_{\text{N3384}, \text{bulge}} \nu_{\text{N3384}, \text{bulge}} + w_{\text{N3384}, \text{disk}} \nu_{\text{N3384}, \text{disk}} + w_{\text{M105}, \text{Ser}} \nu_{\text{M105}, \text{Ser}} + w_{\text{M105}, \text{Exp}} \nu_{\text{M105}, \text{Exp}} \]

The total likelihood is the product of the individual likelihoods calculated for each individual PN with coordinates (RA, Dec) and LOS velocity \( v \pm \delta v \):

\[ L = \prod_{k=0}^{N} L_k \]

This method allows us to exploit the information available for every PN without the explicit need for binning in velocity space. As discussed in Sects. 3.1 and 3.2, we evaluate the five LOSVD parameters \( v_{\text{rot}}, \sigma_r, \sigma_{\text{N3384}, \text{bulge}}, \sigma_{\text{M105}, \text{Ser}}, \) and \( \sigma_{\text{M105}, \text{Exp}} \) independently in five elliptical annuli centred on the respective galaxies (solid and dashed ellipses in Fig. 9). This results in a parameter space of 25 dimensions, which is explored using the ensemble-based MCMC sampler EMCEE (Foreman-Mackey et al. 2013).

3.6. Priors and posteriors

As Cortesi et al. (2013b) already carried out a bulge–disk decomposition of NGC 3384 based on the single PN.S field available to them at the time, we use their best-fit parameters and corresponding errors as Gaussian priors on \( v_{\text{rot}}, \sigma_r, \sigma_{\text{N3384}, \text{bulge}} \). As we evaluate the LOSVD in five elliptical bins instead of three, we interpolated their best-fit profiles as a function of radius and used the interpolated values at the bin centres. An example of the Gaussian priors for the innermost of the five elliptical bins is indicated with red solid lines in Fig. 8. We place uniform priors on \( \sigma_{\text{M105}, \text{Ser}} \) and \( \sigma_{\text{M105}, \text{Exp}} \), but require \( \sigma_{\text{M105}, \text{Ser}} \leq \sigma_{\text{M105}, \text{Exp}} \) in each of the bins.

The posterior probability distributions are calculated with EMCEE (Foreman-Mackey et al. 2013) using 52 walkers \((2N_{\text{dim}} + 2)\) and 2000 steps. Figure 8 shows the resulting distributions visualised as a corner plot for the innermost of the five elliptical bins. This is a convenient representation of a subset of the parameter space. However, we stress that the 25-dimensional space is explored simultaneously for data over the entire radial range. The best-fit parameters and their errors are the 50\% and (16\%, 84\%) quantiles. While the best-fit parameters give a good first estimate of the LOS velocity dispersion of the Sérsic and exponential PN populations in the halo of M 105, we calculate more accurate radial velocity dispersion profiles with robust methods and based on the final membership assignment presented in the following.
3.7. Final membership assignment

For each PN, we determine the probabilistic fraction $f_i$ to belong to one of the four populations (the disk and bulge of NGC 3384, and the Sérsic and exponential halos of M 105) based on its position and LOS velocity. Figure 9a illustrates the probability space populated by our observations, with $f_{\text{M105,Ser}} > 0.5$ coloured in orange (138 PNe), $f_{\text{M105,Exp}} > 0.5$ coloured in purple (31 PNe), and $f_{\text{NGC3384,bulge}} > 0.5$ being represented by crosses on a red-to-blue colour scale with red colours for $f_{\text{NGC3384,bulge}} > 0.5$ (37 PNe) and blue colours for $f_{\text{NGC3384,disk}} > 0.5$ (56 PNe). Points that cannot be uniquely associated with any of the four components outlined previously are colour-coded in grey (7 PNe). Figure 9b shows the distribution of PNe colour-coded by $f_i$ in position-space, and Fig. 9c,d in phase-space along the major and minor axes of M 105, respectively.
Both in position- and phase-space, PNe can be robustly separated into those associated with M 105 and those with NGC 3384. This is important for the study of the LOSVD of M 105, which is presented in the following sections. We maximised the number of PNe to be considered for follow-up analysis compared to conventional cuts in position space (as e.g., done by Douglas et al. 2007), while ensuring that the derived LOSVDs are of sufficient quality. The final column of Table A.2 provides the probabilistic fraction to be assigned to M 105 \( f_{\text{M 105}} = f_{\text{M 105, Ser}} + f_{\text{M 105, Exp}} \) for each PN in the final sample. This can be easily translated to the probabilistic fraction to be assigned to NGC 3384 \( f_{\text{NGC 3384}} = 1 - f_{\text{M 105}} \).

4. Kinematics in the outer halo of M 105

In the following section, we only consider PNe that we assigned to the M 105 halo and envelope in the previous section. For the calculation of the smoothed 2D velocity and velocity dispersion fields and the extraction of the rotation profiles, we assume that M 105 is point-symmetric in the position-velocity phase-space, as commonly done when constructing velocity fields based on PN kinematics (e.g., Arnaboldi et al. 1998; Coccato et al. 2009; Pulsoni et al. 2018). This implies that each point \((x, y, v)\) in this phase-space has a ‘mirror point’ \((-x, -y, -v)\) and that the number of data points with which the kinematic quantities are calculated...
4.1. Smoothed 2D velocity and velocity dispersion fields

We calculate kernel-smoothed velocity and velocity dispersion fields for all PNe associated with M 105 and for the Sérsic and exponential components separately from the folded catalogues. We use a distance-dependent Gaussian kernel as defined in Coccato et al. (2009)

\[ w_i = \exp \left( -\frac{D_i^2}{2k(x_i,y_i)^2} \right), \]

where the kernel width \( k(x,y) \) is proportional to the distance \( R_{i,M} \) to the \( M \)th closest tracers located at \((x_M,y_M)\):

\[ k(x_i,y_i) = AR_{i,M}(x_M,y_M) + B. \]

We use the optimised kernel parameters \( A = 0.34 \) and \( B = 16.2 \) for the \( M = 20 \) closest tracers, which were determined by Pulsoni et al. (2018) based on Monte Carlo simulations of discrete velocity fields, allowing for the best compromise between noise smoothing and spatial resolution.

Figure 10 shows the resulting smoothed velocity \( v_s \) (top row) and velocity dispersion \( \sigma_s \) fields (bottom row) for all PNe associated with M 105 in the left column, and the Sérsic and exponential components shown in the middle and right columns, respectively. The smoothed velocity and velocity dispersion fields of the Sérsic and exponential components show distinct features. As expected from the method with which PNe were associated to either component, the LOS velocity dispersion of PNe in the exponential component is much larger than that of those in the Sérsic one, even at comparable radial ranges. The rotation signatures in the velocities are also different, suggesting that different mechanisms contributed to the formation of the Sérsic and exponential components in the halo of M 105.

4.2. Line-of-sight velocity dispersion profiles

To determine the LOS velocity dispersion profiles, we again only consider PNe with \( f_{M,105,Ser} \) and \( f_{M,105,Exp} > 0.5 \), that is, PNe firmly associated with M 105 and the exponential envelope both in position and velocity space. We already obtained velocity dispersions in the five elliptical bins from the likelihood analysis presented in Sect. 3.7 for the Sérsic and exponential components separately. However, to explore a finer resolution along the radial direction and be more robust to potential outliers, we...
which the PN number density starts to flatten due to a higher $\alpha$

We first assess the di-

The strong decline of the LOS velocity dispersion in


to the exponential envelope (indicated by

as well as with SAURON integral-field spectroscopic data

Weijmans et al. (2009).

The velocity dispersion increases strongly beyond 400" (cor-

responding to $\approx 7.5 R_{\text{e}}$), which also corresponds to the radius at

which the PN number density starts to flatten due to a higher $\alpha$

parameter value at large radii, as indicated by the dotted vertical

line. The rise in the LOS velocity at large radii is thus driven by PNe

associated with the exponential envelope (indicated by purple triangles on Fig. 11). These PNe have a larger LOS velocity dispersion than those associated with the Sérsic halo (orange squares). The strong decline of the LOS velocity dispersion in the inner halo is instead driven by PNe associated with the latter component.

4.3. Rotation

We first assess the different rotation signatures by separately fitting rotation curves to the smoothed velocities $v_{\text{r}}$ for the Sérsic and exponential populations separately as a function of position angle $\Theta$ as shown in Fig. 12, excluding the 2$\sigma$ outliers identified in the previous Sect. 4.2 from further analysis. Following Pulsoni et al. (2018), we fit the mean velocity fields with the following function:

$$v_{\text{r}}(R, \Theta) = v_{\text{sys}}(R) + v_{\text{rot}}(R) \cos(\Theta - \Theta_{\text{sys}}(R))$$

$$+ s_{1}(R) \sin(3\Theta - 3\Theta_{0}) + a_{1}(R) \cos(3\Theta - 3\Theta_{0}),$$

where $v_{\text{sys}}$ is the systemic velocity, $v_{\text{rot}}$ the amplitude of the rotation, and $\Theta_{0}$ the kinematic position angle with respect to the photometric position angle. These parameters describe the rotation around the kinematic major axis, while $s_{1}$ and $a_{1}$ are the amplitudes of the third-order terms\(^1\).

Figure 12 shows the smoothed velocity as a function of the position angle $\Theta$ for the observed PNe in each of the two components. We fit rotation profiles to these data, only considering the azimuthal dependence of Eq. (19). We evaluate whether the goodness of the fit is improved by including the higher order terms with amplitudes $a_{1}$ and $s_{1}$ using the Bayesian information criterion (BIC). Table 3 summarises the best-fit parameters fit to the velocity fields, and the resulting best-fit rotation curves are shown in Fig. 12. Models including higher moments are preferred for both components. In the case of the Sérsic component, the fit with higher moments has both lower BIC and reduced $\chi^{2}$ values. For the exponential envelope, the BIC values are indistinguishable, but the fit with higher moments has a lower reduced $\chi^{2}$ value.

The Sérsic component has a rotation amplitude of $v_{\text{rot},\text{Ser}} = 16.0 \pm 1.8$ km s$^{-1}$ and a kinematic major axis that is aligned with the photometric major axis within the errors. This component also has a systemic velocity of $v_{\text{sys},\text{Ser}} = 935.1 \pm 1.4$ km s$^{-1}$ that agrees with that determined by Pulsoni et al. (2018) based on the central field of M 105. In contrast to this, the rotation amplitude of the PNe in the exponential envelope is more than three times higher, being $v_{\text{rot},\text{Exp}} = 49.2 \pm 6.7$ km s$^{-1}$, and the kinematic major axis is aligned with the photometric minor axis of M 105, while their systemic velocity of $v_{\text{sys},\text{Exp}} = 934.2 \pm 9.9$ km s$^{-1}$ agrees with that of the Sérsic component within the errors. To visualise \(^1\) As we assume that the phase-space is point-symmetric, this prohibits even contributions to the higher-order terms.
the on-sky orientation of the photometric and kinematic major axes, they are overplotted on top of the smoothed velocity fields in Fig. 10.

To evaluate the radial dependence of the rotation profile, we again fitted Eq. (19) to the data, but in elliptical bins, for all PNe associated with M 105. We also fitted Eq. (16) to the Sérsic and exponential populations separately. Because of the smaller number of tracers per bin, we did not fit the third-order modes, as this led to noisier fits. The resulting best-fit profiles of the rotation amplitude \( \psi_{\text{rot}} \), systemic velocity \( \psi_{\text{sys}} \), and kinematic position angle \( \Theta \) are shown in Fig. 13 from top to bottom. As already observed by Pulsoni et al. (2018), the rotation amplitude decreases in the inner halo with hints for growing rotation in the outskirts. This decrease was also inferred from long-slit spectroscopy (Statler & Smoker-Hane 1999). Our new extended data reveal that there is a transition region where the rotation amplitude remains small, followed by a strong increase of the rotation amplitude in the exponential envelope which is driven by the PNe associated with this component (purple diamonds).

This transition goes hand in hand with a twisting of the kinematic position angle that is illustrated in the bottom panel of Fig. 13. In the inner halo, where the Sérsic population dominates, the kinematic position angle is aligned with the photometric one. In contrast, in the outer halo, the position angle twists by more than 90° and is more or less aligned with the photometric minor axis of the inner high SB regions.

4.4. Angular-momentum content

Emselelem et al. (2007) introduced a kinematic classification scheme for galaxies based on the so-called \( \lambda_R \) parameter, which quantifies rotational support and can be used as a proxy to quantify the observed projected stellar angular momentum. To infer the angular momentum content locally, i.e. in elliptical bins with mean radius \( R_{\text{mean}} \) and bin edges \( R_{\text{min}} \) and \( R_{\text{max}} \), \( \lambda_R \) can be calculated from the smoothed velocity and velocity dispersion fields \( V \) and \( \sigma \):

\[
\lambda_R(R_{\text{mean}}) = \frac{\sum_{R=R_{\text{min}}}^{R_{\text{max}}} R_i |V_i|}{\sum_{R=R_{\text{min}}}^{R_{\text{max}}} R_i \sqrt{\sigma_i^2 + \sigma_{i,\text{geo}}^2}}. \tag{20}
\]

The cumulative \( \lambda_R \) profiles are instead calculated from the centre of the galaxy to the outer bin edge \( R_{\text{max}} \) and corrected for geometric incompleteness \( \epsilon_{\text{geo}} \):

\[
\lambda_R(< R_{\text{max}}) = \frac{\sum_{R=R_{\text{min}}}^{R_{\text{max}}} R_i |V_i| / \epsilon_{\text{geo}}}{\sum_{R=R_{\text{min}}}^{R_{\text{max}}} R_i / \epsilon_{\text{geo}} \sqrt{\sigma_i^2 + \sigma_{i,\text{geo}}^2}}. \tag{21}
\]

The cumulative \( \lambda_R \) is weighted by the flux associated with each radial bin. For PNe, this is implicitly incorporated as the PN number density traces the light distribution (Coccato et al. 2009). When ordered motion dominates (i.e. rotation), \( \lambda_R \) approaches unity. Within one effective radius, \( \lambda_R \) can be used as a proxy to divide galaxies into the categories of fast \((\lambda_R > 0.1)\) and slow rotators \((\lambda_R < 0.1)\). M 105 has been classified as a fast rotator (Emselelem et al. 2007; Coccato et al. 2009; Pulsoni et al. 2018).

The left panel of Fig. 14 shows the local \( \lambda_R \) profiles for all PNe associated with M 105, the Sérsic halo, and the exponential envelope, evaluated in the same elliptical annuli as used in Figs. 13 and 11. In the inner halo, the kinematic transition radius identified by Pulsoni et al. (2018) is marked by a decrease in the local \( \lambda_R \) profile, which persists until \( \sim 2 R_{\text{eff}} \). At \( \sim 4 R_{\text{eff}} \), the \( \lambda_R \) profile peaks again. At large radii, that is, in the exponential envelope, \( \lambda_R \) increases, reaching values of \( \lambda_R = 0.4 \) in the outermost bin. The right panel of Fig. 14 shows the cumulative \( \lambda_R \) profiles. Based on the two panels, we identify three distinct kinematic components, which are discussed further in the following section: the rotating core within \( 1 R_{\text{eff}} \), the halo from \( 1 R_{\text{eff}} \) to \( 7.5 R_{\text{eff}} \), and the exponential envelope from \( 7.5 R_{\text{eff}} \) to the last data point at \( 16 R_{\text{eff}} \).

5. Discussion

In this work, we efficiently associated PNe in the Leo I group to different subpopulations in the velocity phase-space centred on M 105. Vital for measuring the LOS kinematics at large radii from the centre of M 105 was the division of
Table 3. Best-fit parameters for the rotation models fit to the Sérsic and exponential velocity fields.

<table>
<thead>
<tr>
<th>Component</th>
<th>Higher modes</th>
<th>$\Theta_0^{(a)}$ [xπ]</th>
<th>$v_{sys}^{(b)}$ [km s$^{-1}$]</th>
<th>$v_{rot}$ [km s$^{-1}$]</th>
<th>$s_1$ [km s$^{-1}$]</th>
<th>$a_1$ [km s$^{-1}$]</th>
<th>BIC</th>
<th>$\chi^2_{red}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sérsic</td>
<td>Y</td>
<td>0.00 ± 0.13</td>
<td>935.1 ± 1.4</td>
<td>15.9 ± 1.9</td>
<td>-6.46 ± 5.66</td>
<td>13.3 ± 3.1</td>
<td>-10.6</td>
<td>153.6</td>
</tr>
<tr>
<td>Sérsic</td>
<td>N</td>
<td>0.00 ± 0.02</td>
<td>933.7 ± 1.5</td>
<td>15.5 ± 2.0</td>
<td>-6.46 ± 5.66</td>
<td>13.3 ± 3.1</td>
<td>28.4</td>
<td>200.2</td>
</tr>
<tr>
<td>Exponential</td>
<td>Y</td>
<td>0.48 ± 0.09</td>
<td>934.2 ± 9.9</td>
<td>49.3 ± 8.1</td>
<td>8.79 ± 14.30</td>
<td>16.3 ± 8.4</td>
<td>30.0</td>
<td>44.1</td>
</tr>
<tr>
<td>Exponential</td>
<td>N</td>
<td>0.56 ± 0.09</td>
<td>925.9 ± 9.0</td>
<td>49.8 ± 8.0</td>
<td>8.79 ± 14.30</td>
<td>16.3 ± 8.4</td>
<td>29.8</td>
<td>56.1</td>
</tr>
</tbody>
</table>

Notes. $^{(a)}$The kinematic position angle was determined with respect to the photometric position angle. $^{(b)}$The systemic velocity determined by Pulsoni et al. (2018) based on the M 105-C field is $v_{sys,M105} = 934 ± 14$ km s$^{-1}$.

5.1. Metal-rich and intermediate-metallicity populations in the inner halo of M 105

Pulsoni et al. (2018) identified a kinematic transition in the inner halo at $R_{eff}$, which is marked by a decrease in the rotation amplitude (Fig. 13), the LOS velocity dispersion (Fig. 11), and the local $\lambda_{g}$ parameter (Fig. 14) with radius. The first kinematic component of M 105 that we identified is thus the rotating core in the centre of the galaxy. Our measurements of $V$ and $\sigma$ agree with those of Weijmans et al. (2009) based on SAURON integral-field spectroscopy in the regions of overlap and the long-slit data from Statler & Smecker-Hane (1999). Weijmans et al. (2009) inferred an age of $\approx$12 Gyr and approximately solar metallicity for the rotating core.

Beyond the transition at $R_{eff}$, the metallicity decreases, reaching 20% of the solar value, i.e. $[\alpha/Fe] = -0.7$ at $3-4R_{eff}$ (Weijmans et al. 2009), which is similar to the peak of the metallicity distribution function in the inner HST field located at $4 \leq R_{eff} \leq 6$ to the northeast of the centre of M 105 (Lee & Jang 2016, see also the hatched regions in the right panel of Fig. 1). The PN population in the inner halo is characterised by a low $\alpha$-parameter $\alpha_{2,S,M105,IM} = (1.00 \pm 0.11) \times 10^{-8} \text{PN L}^{-1}$ and a shallow PNLF slope, albeit still steeper than the ‘standard’ Ciardullo et al. (1989) PNLF (H+2020).

In the $\lambda_{g}$ profile shown in Fig. 14, a second peak is visible at around $4R_{eff}$. This peak is due to an increase in rotation at these radii, while the LOS velocity dispersion profile monotonously declines in the inner halo. This peak is co-spatial with a change in position angle of the isophotes of M 105 and an increased ellipticity (Ragusa et al. 2022) and may be related to a secondary rotating component, revisiting the original suggestion of Capaccioli et al. (1991) that M 105 may be a S0 galaxy observed face-on.

Based on results from the IllustrisTNG cosmological hydrodynamical simulations, Pulsoni et al. (2021) argued that the observed kinematic transition radii do not trace the transition between in situ and ex situ dominated regions. The innermost transition radius at $R_{eff}$ therefore does not necessarily represent a transition to a component dominated by accreted stars. Instead, the characteristic peaked and outwardly decreasing rotation profile of stars in the inner halo (see top panel of Fig. 13) is similar to that of the in situ stars in low-mass ETGs in cosmological hydrodynamical simulations (Pulsoni et al. 2021).

The more extended PN.S data in the halo of M 105 allowed us to reveal a second kinematic transition at $\approx$7.5$R_{eff}$, where both...
the LOS velocity dispersion and the rotation amplitude increase significantly. These increases are driven by the exponential envelope; a population of PNe associated with a metal-poor population ([M/H] < −1) of RGB stars following an exponential SB profile (H+2020). As M 105 is a member of the Leo I group, we now place these findings in the context of the kinematics of the group at large.

The increase in the velocity dispersion at large radii may indicate that PNe in the exponential envelope of M 105 are bound to the gravitational potential of the Leo I group and thus part of its IGL. We therefore compare the kinematics in the outer halo of M 105 with that of satellite galaxies in the Leo I group. We use the compilation of Müller et al. (2018, see Table A.4) and selected dwarf galaxies in the M 96 subgroup with LOS velocity measurements (from Ferguson et al. 1998; Staveley-Smith et al. 1992; Huchtmeier et al. 2003; Karachentsev et al. 2004, 2013; Karachentsev & Karachentseva 2004; Haynes et al. 2011). Unfortunately, the majority of the dwarf galaxies in this sample did not have accurate (if any) distance measurements. With this caveat in mind, we fitted the overall rotation profile and determined the LOS velocity dispersion of these 27 galaxies. The bottom panel of Fig. 12 shows their unsmoothed LOS velocities colour coded by the on-sky distance to the centre of M 105. We fitted Eq. (19) to the data to determine a best-fit systemic velocity $v_{\text{sys,Leo1}} = 850 \pm 35 \, \text{km s}^{-1}$ (dotted horizontal line on Fig. 12), which is lower than that of the PNe in the Sérsic halo of M 105 $v_{\text{sys,Ser}} = 935.1 \pm 1.4 \, \text{km s}^{-1}$ and in the exponential envelope $v_{\text{sys,Exp}} = 934.2 \pm 9.9 \, \text{km s}^{-1}$. The rotation amplitude of the dwarf galaxies $v_{\text{rot,Leo1}} = 148 \pm 53 \, \text{km s}^{-1}$ is significantly larger than that in the outer halo of M 105 (83 ± 5 km s$^{-1}$ at the last data point). The kinematic position angle of the dwarf galaxies is PA = 125 ± 17° (dashed vertical line), which is nearly aligned with the photometric minor axis of the inner high SB region of M 105 and thus also with the kinematic position angle of the exponential envelope, within the errors. The best fit is indicated by the solid grey line in the bottom panel of Fig. 12.

The blue error bars in the right panel of Fig. 11 denote the LOS velocity dispersion of the dwarf galaxies that was determined in three elliptical bins with the same position angle and ellipticity as used when binning the PN data. The LOS velocity dispersion of PNe tracing the exponential envelope (purple diamonds) reaches that of the Leo I group as traced by the dwarf galaxies. This indicates that both the PNe in the exponential envelope and the surrounding dwarf galaxies trace the group potential. This is corroborated by the similar rotation properties (cf. Fig. 12).

The increase in LOS velocity dispersion profile at large radii inferred from PNe is corroborated by velocity measurements of globular clusters (GCs). Bergond et al. (2006) obtained radial velocities of 42 GCs in the Leo I group, of which they associated 30 with M 105, and combined those with previous velocity measurements of 8 GCs centred on M 105 (Puzia et al. 2004). The LOS velocity dispersion measurement of Bergond et al. (2006) is indicated by green triangles with error bars in the left panel of Fig. 11. At large radii, the measurements from GCs and PNe are in excellent agreement, while the velocity dispersion measured from GCs in the inner halo is larger than that from PNe. This is expected, because the GCs have a shallower number density profile than the PNe at these radii (Puzia et al. 2004; Bergond et al. 2006). Dividing the sample by colour into blue (and metal-poor) and red (and metal-rich) GCs, Puzia et al. (2004) find the blue GCs to have a shallower number density profile than the red ones, and in agreement with the measurements from resolved stellar populations (Lee & Jang 2016) the fraction of blue and metal-poor GCs increases with radius (Bergond et al. 2006). Because of the small number of GC radial velocities around M 105, it is not possible to robustly establish whether the projected rotation of the GCs, which is co-spatial with the exponential outer envelope, is consistent with that measured using PNe.

Similar trends of increasing LOS velocity dispersion profiles have been observed for discrete tracers such as PNe and GCs of the IGL or intra-cluster light (ICL) in the Virgo (Hartke et al. 2018; Longobardi et al. 2018a,b) and Fornax Clusters (Spiniello et al. 2018; Pota et al. 2018), as well as based on integrated light in more distant clusters (Dressler 1979; Kelson et al. 2002; Bender et al. 2015). While the ICL fraction in these environments is much higher and measured at higher
SB levels than that in the Leo I group, the kinematic signature of halo-to-ICL transition is the same in the low-mass Leo I group. H+2020 argued that the high $\alpha$-parameter value and steeper PNLF slope of the exponential envelope traced by the metal-poor stellar population is indicative of a distinct origin compared to the more metal-rich main halo. Furthermore, the metallicity distribution function of RGB stars in the western HST field in the outer halo (Harris et al. 2007b; Lee & Jang 2016) resembles that of the resolved intra-cluster RGB stars in the Virgo Cluster core (Williams et al. 2007). Combined with the stellar kinematics discussed previously, we therefore conclude that the population of PNe associated with the metal-poor exponential envelope traces the IGL of the Leo I group.

5.3. Halo and IGL formation scenarios

Lee & Jang (2016) proposed a two-mode formation scenario for the metal-rich and metal-poor stellar populations in M 105, in which the metal-rich inner halo was formed in situ or through major mergers or relatively massive and thus metal-rich progenitors. Later, the blue and metal-poor halo that we identify as the exponential envelope in this work was assembled through dissipationless mergers and accretion. In addition to the inferences based on their metal-rich nature, the kinematics of stars in the inner halo point towards an in situ origin, or they may have been brought in through a few massive and ancient mergers. The outwardly decreasing rotation and LOS velocity dispersion profiles are similar to those of in situ stars in massive ETGs in cosmological hydrodynamical simulations such as IllustrisTNG (Pulsoni et al. 2021). The formation of the metal-rich inner stellar halo through massive and ancient mergers is also observed in IllustrisTNG (Zhu et al. 2022). The PN population properties, such as the lower $\alpha$-parameter value and shallower PNLF slope, are consistent with relatively massive and old parent stellar populations (Buzzoni et al. 2006).

The blue and metal-poor exponential envelope instead is traced by a PN-rich population, whose high $\alpha$-parameter value is similar to that of Local Group dwarf irregular galaxies (such as Leo I, and Sextans A and B; Buzzoni et al. 2006). The high velocity dispersion and moderate rotation of these PNe corroborate the late accretion scenario of Lee & Jang (2016). Lastly, H+2020 already noted that their luminosity estimate for the exponential envelope ($2.04 \times 10^9 L_\odot$) is similar to the luminosity of single ultra-faint galaxies (UFGs) in group and cluster environments (Miho et al. 2015). Lee & Jang (2016) postulate that UFGs are strong candidates to be responsible for the metal-poor stellar population in the exponential envelope of M 105, as they have comparable metallicity distribution functions (e.g., Jang & Lee 2014). Because of their low mass and density, UFGs are easily stripped, and their debris can be deposited at large radii from the massive ETG (Amorisco 2017), making them viable progenitors of the IGL stars.

5.4. The case of the ICL surrounding M 49 in the Virgo Cluster

Hartke et al. (2017) showed that PN populations in the inner halo (within 60 kpc, corresponding to $\approx 2.8 R_{\text{eff}}$) and the outskirts of the ETG M 49 in the massive ($10^{12} M_\odot$) Virgo Cluster have distinct spatial distributions and arise from stellar populations with different $\alpha$-parameters and with distinct PNLF slopes. Based on data from the PN S, Hartke et al. (2018) also showed that bright and faint PN populations have distinct kinematics, with the faint population tracing the transition to the ICL of the Virgo Subcluster B signalled by an increase in the LOS velocity dispersion as a function of radius, reaching that of satellite galaxies orbiting the subcluster at large radii.

In the case of M 49, Hartke et al. (2018) had to rely on the combination of galaxy colours and PN dynamics to infer a link between the high $\alpha$-parameter measured in the transition region between the halo and ICL and an old, metal-poor underlying stellar population to explain the blue colours observed in the outer halo of M 49 (Mihos et al. 2013). However, by studying the nearby galaxy M 105 in the much less massive ($4.7 \times 10^{11} M_\odot$; Kourkchi & Tully 2017) Leo I group of galaxies, it is now possible to unambiguously link the presence of a PN population with a high $\alpha$-parameter (H+2020) to a co-spatial metal-poor stellar population forming part of the IGL of the Leo I group.

6. Summary and conclusions

In this paper, we present a new wide-field kinematic survey of PNe in the Leo I group. We discuss the sample selection and catalogue construction, as well as the overlap with previous photometric and kinematic surveys. The photometric and kinematic catalogues are included in Appendix A and are available in electronic form at the CDS. We have separated PNe into populations associated with the bulge and disk of the group galaxy NGC 3384, and with the Sérsic halo and exponential envelope of our main target, M 105.

We identify three kinematically distinct populations of PNe in the halo of M 105, whose properties can be summarised in turn, as follows:

1. The rotating core within $1 R_{\text{eff}}$ (2.7 kpc), characterised by a solar-metallicity stellar population that was likely formed in situ.
2. The inner halo, from $1 R_{\text{eff}}$ to $7.5 R_{\text{eff}}$ (2.7–20.25 kpc), made up by old intermediate-metallicity and metal-rich stars and characterised by low rotation and LOS velocity dispersion PNe with a low $\alpha$-parameter. The inner halo was either entirely formed in situ, or through notable contributions from massive and metal-rich merging events.
3. The exponential envelope, from $7.5 R_{\text{eff}}$ (20.25 kpc) to the last data point at $16 R_{\text{eff}}$ (43.2 kpc), containing a metal-poor and PN-rich stellar population with increasing rotation and constantly high LOS velocity dispersion. The exponential envelope was formed through dissipationless mergers and accretion of dwarf galaxies and very likely forms part of the extended IGL of the Leo I group.

Future work will focus on dynamical modelling of the PN subpopulations to determine the mass and orbital anisotropy profile of M 105 and its group environment. We also carry out an in-depth comparison of the kinematic transitions identified in this work with new deep photometry. Lastly, this data set will also allow us to investigate changes of the PNLF bright cut-off for the kinematically distinct populations of PNe in the inner halo and exponential envelope.

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Appendix A: Tabular data

In this Appendix we present the catalogues of PNe observed in the Leo I group with Surprime-Cam at Subaru Telescope and the PN.S at the William Herschel Telescope. Table A.1 provides the IDs, coordinates (J2000 with the 2MASS catalogue as astrometric reference), and $AB$ [O III] and $V$-band magnitudes of all PN candidates brighter than the limiting magnitude $m_{5007,\text{lim}} = 28.1$, which were discovered based on Surprime-Cam observations. The survey objectives, data reduction, and PN candidate identification and validation are described in detail in the companion paper H+2020 and briefly summarised in Sect. 2.1 of this work.

Table A.1 provides the IDs, coordinates (J2000 with the 2MASS catalogue as astrometric reference), $AB$ [O III] magnitudes, LOS velocities, and corresponding errors, as well as the membership probability to be associated with M 105 (see Sect. 3). Two concatenated IDs denote PNe that were observed in two fields, and objects with IDs starting with M 105-C and N3384 were observed first by Douglas et al. (2007) and Cortesi et al. (2013a) respectively. The catalogue only contains PNe with velocities within $3\sigma$ about the robust mean (see Sect. 2.2.1). The full tables are only available in electronic form at the CDS.

Table A.1. IDs, coordinates, and magnitudes of PN candidates from Surprime-Cam photometry (H+2020). Only objects brighter than the limiting magnitude are included. The full table is only available in electronic form at the CDS.

<table>
<thead>
<tr>
<th>ID</th>
<th>RA [hh:mm:ss] (J2000)</th>
<th>dec [°:′:″] (J2000)</th>
<th>$m_{[\text{O\ III}],AB}$ [mag]</th>
<th>$V_{AB}$ [mag]</th>
</tr>
</thead>
<tbody>
<tr>
<td>M 105-SCAM-002</td>
<td>10:47:40.7357</td>
<td>12:23:33.2999</td>
<td>25.0</td>
<td>26.4</td>
</tr>
<tr>
<td>M 105-SCAM-003</td>
<td>10:47:29.4416</td>
<td>12:23:45.1158</td>
<td>25.1</td>
<td>27.3</td>
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<tr>
<td>...</td>
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<td>...</td>
</tr>
</tbody>
</table>

Table A.2. IDs, coordinates, magnitudes, velocities and membership probabilities of PNe in the Leo I galaxies M 105 and NGC 3384. Objects with IDs starting with M 105-C and N3384 were observed first by Douglas et al. (2007) and Cortesi et al. (2013a) respectively. Two concatenated IDs denote PNe that were observed in two fields. The catalogue only contains PNe with velocities within $3\sigma$ about the robust mean (see Sect. 2.2.1). The full table is only available in electronic form at the CDS.

<table>
<thead>
<tr>
<th>ID</th>
<th>RA [hh:mm:ss] (J2000)</th>
<th>dec [°:′:″] (J2000)</th>
<th>$m_{[\text{O\ III}],AB}$ [mag]</th>
<th>$v_{\text{los}}$ [km s$^{-1}$]</th>
<th>$\Delta v_{\text{los}}$ [km s$^{-1}$]</th>
<th>$f_{M\ 105}$</th>
</tr>
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<tr>
<td>M 105-C001_M 105-W001</td>
<td>10:47:31.1951</td>
<td>12:39:20.1428</td>
<td>24.9</td>
<td>1002.0</td>
<td>19.1</td>
<td>0.99631</td>
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<tr>
<td>M 105-C002</td>
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<td>12:32:09.7428</td>
<td>24.3</td>
<td>909.0</td>
<td>20.0</td>
<td>0.99354</td>
</tr>
<tr>
<td>M 105-C003</td>
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<td>12:34:08.5428</td>
<td>25.4</td>
<td>892.0</td>
<td>20.0</td>
<td>0.99072</td>
</tr>
<tr>
<td>...</td>
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<td>...</td>
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<td>...</td>
<td>...</td>
</tr>
<tr>
<td>N3384-C093</td>
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<td>12:36:27.0622</td>
<td>23.8</td>
<td>629.0</td>
<td>20.0</td>
<td>0.01520</td>
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