THE LINE-OF-SIGHT VELOCITY DISTRIBUTIONS OF INTRACLUSTER PLANETARY NEBULAE IN THE VIRGO CLUSTER CORE

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ABSTRACT

Radial velocities of 40 intracluster planetary nebulae (ICPNe) in the Virgo cluster were obtained with the new multi-fiber FLAMES spectrograph on UT2 at VLT. For the first time, the $\lambda 4959$ Å line of the [OIII] doublet is seen in a large fraction (50%) of ICPNe spectra, and a large fraction of the photometric candidates with $m(5007) \lesssim 27.2$ is spectroscopically confirmed.

ICPNe with the velocity dispersion of the Virgo cluster are found in our CORE field 1.2 from M87. These may have originated from tidal mass loss of smaller galaxies in the M87 subcluster halo. In a field 0.25 deg from M87, we see an extended stellar halo of M87 in approximate dynamical equilibrium, but with few ICPNe. Finally, in a field near M84/M86, the ICPNe velocities are highly correlated with the galaxy velocities, showing that any well-mixed intracluster population is yet to form. Overall, the measured velocity distributions confirm the non-uniform dynamical structure and on-going assembly of the Virgo cluster.

Subject headings: (ISM:) planetary nebulae: general; galaxies: cluster: general; galaxies: cluster: individual (Virgo cluster); galaxies: evolution

1. INTRODUCTION

After the serendipitous discovery of intracluster planetary nebulae (ICPNe) in the Virgo (Arnaboldi et al. 1996) and Fornax (Theuns & Warren 1997) clusters, our group embarked on a systematic study of the diffuse stellar population in the Virgo cluster. The aim of this research is to measure the fraction of cluster stars between galaxies, their radial distribution, and their motions. The discovery of ICPNe, the subsequent narrow band imaging surveys to find ICPN samples (Feldmeier et al. 1998, 2003a; Arnaboldi et al. 2002, 2003; Okamura et al. 2002), and the HST observations of Virgo cluster empty fields (Ferguson et al. 1998; Durrell et al. 2002) have revitalized the study of diffuse intracluster light (ICL). The preliminary results on the systematics of the ICL in different environments, from loose groups to rich clusters (Gonzalez et al. 2000, Gal-Yam et al. 2003, Castro-Rodriguez et al. 2003, Feldmeier et al. 2003b), and the predictions from recent cosmological N-body and hydrodynamical simulations (Napolitano et al. 2003, Murante et al. 2004, Sommer-Larsen et al. 2004, Willman et al. 2004) have proven the study of the ICL as a valuable tool to investigate galaxy and galaxy cluster evolution.

ICPNe are the only component of the ICL whose kinematics can be measured at this time. This is important since the high-resolution N-body and hydrodynamical simulations predict that the ICL is unrelaxed, showing significant substructure in its spatial and velocity distributions in clusters similar to Virgo. While spatial structures have been observed in the ICPN number density distribution both in a single field (Okamura et al. 2002) and as field-to-field variations (Aguerri et al. 2002), substructure in velocity space still needs to be investigated.

Early attempts by Freeman et al. (2000) with the AAT and 2DF spectrograph provided only a few spectroscopically confirmed emission line objects in the Virgo cluster core. Their identification as ICPNe relies on the presence of the weaker [OIII] line ($\lambda 4959\AA$) in the summed spectrum of all the detected single-line candidates. Because modern emission line candidate samples in Virgo contain a modest fraction of Ly$\alpha$ emitters at $z = 3.1$ (Aguerri et al. 2004), spectral identification of ICPN either needs high spectral resolution to resolve the typical broad, asymmetric Ly$\alpha$ lines, and/or detection of the [OIII] $\lambda 4959/5007\AA$ doublet. 1

ICPNe samples are sparse, with only a few tens of ICPNe in a 0.25 deg$^2$ field, and their fluxes are faint, from $1 \times 10^{-16}$ to $5 \times 10^{-17}$ erg cm$^{-2}$ s$^{-1}$ in the [OIII] 5007 Å line. Spectroscopic observations thus require 8 meter class telescopes and spectrographs within a field-of-view (FOV), of a fraction of a square degree. The [OIII] emission lines from PNe are only a few km s$^{-1}$ wide, so relatively high resolution spectra ($R = 7000$ to $10,000$) are desirable to reduce the sky contamination. The FLAMES-GIRAFFE spectrograph on VLT, with its medium-high spectral resolution, its FOV of 25 arcmin in diameter and 130 fibers in the MEDUSA mode, is therefore very well suited to this project. Here we present the results of the spectroscopic follow-up with FLAMES of the ICPN candidates selected from three survey fields in the Virgo cluster core.

$^1$ The emission line sample of Kudritzki et al. (2000) was even dominated by Ly$\alpha$ emitters; however, the luminosity function (LF) of this sample follows the LF of Ly$\alpha$ emitters in blank field surveys, not that of ICPNe in Virgo (Castro-Rodriguez et al. 2003).
2. OBSERVATIONS

Table 1 gives the three selected fields in the Virgo core, referred to as FCJ, CORE, and SUB (Aguerri et al. 2004). Spectra were acquired in service mode (10 hrs were allocated to this observing run, 71B-0147, in priority A), with the FLAMES spectrograph at UT2 on VLT in the GIRAFFE+MEDUSA configuration. We used the low resolution grism LR 479.7, covering a wavelength range of 500 Å, centred on 4797 Å, and a spectral resolution of 7500. This gives a velocity resolution of 40 km s⁻¹, and a typical velocity error of 12 km s⁻¹. The redshifted [OIII] emissions of ICPNe in the Virgo cluster core fall near the red edge of the grism response.

The FLAMES FOV covers the FCJ field entirely, and a significant fraction of both CORE and SUB. The total observing time was 2.5 hrs for FCJ, and 2.6 hrs each for CORE and SUB; the exposure times were based on the S/N estimate for detecting the [OIII] 5007 Å line flux of 4.2 × 10⁻¹⁷ erg cm⁻² s⁻¹, i.e. m(5007) = 27.2, with a S/N ∼ 5. Given that the [OIII] 4959/5007 Å emission lines have relative intensities 1:3, we expect to be able to detect the [OIII] 4959 Å emission for the brighter candidates only. The data reduction was carried out with the GIRAFFE pipeline, for CCD pre-reduction, fiber identification, wavelength calibration, geometric distortion corrections, co-addition and extraction of the final 1D-spectra.

Comparing with earlier measurements by Freeman et al. (2000), the RMS velocity difference for four ICPNe in common is 24 km s⁻¹, where their velocity error was 40 km s⁻¹.

3. SPECTROSCOPIC RESULTS

A total of 40 ICPN candidates were detected in the FLAMES spectra. In Fig. 1 we show single ICPN spectra with the [OIII] 4959/5007 Å doublet, and the resolved spectrum of a Lyα galaxy with a broad asymmetric line.

In Table 1 we give results for the three pointings individually. In the FCJ/CORE/SUB fields, we had 18/34/18 fibers allocated to sources brighter or equal to 27.2 and in good regions of the CCD. In total, we detected 15/12/13 sharp line emitters, and 0/2/0 Lyα emitters which show one resolved asymmetric line. The remaining spectra did not show any spectral features in the wavelength range covered by FLAMES. The fraction of confirmed spectra with both components of the [OIII] doublet detected is 67%/41%/18%.

The extracted 1D spectra for the CORE and SUB fields are noisier than those for the FCJ, most probably because the selected reference stars for the FLAMES MEDUSA configuration were not in the astrometric system of the ICPN candidates, therefore fibers were not optimally positioned. For the SUB field, also the observing conditions were slightly worse than for the other fields, resulting in a low fraction of confirmed spectra with detected [OIII] doublet. In the CORE field we checked that the summed spectrum of all sharp line emitters also shows the λ 4959 Å emission in addition to the λ 5007 Å line. The line ratio is 3.5, but with large error because of the noise in the summed spectrum: these spectra are compatible with being all ICPNe.

Table 1 also gives the spectroscopic confirmation rates in the three fields, for candidates down to the brighter of 27.2 or m(5007) from the photometry. This rate varies strongly from field to field despite similar m(5007). The most important reason for this is different contamination of the samples by faint continuum stars, erroneously classified as ICPNe because of a shallow off-band image. Aguerri et al. (2004) investigated the contamination of the photometric samples caused by faint continuum stars, [OIII] emitters at z = 0.347, and high-z emitters, using simulations and blank field surveys. Table 1 shows the expected spectroscopic confirmation rates based on these simulations. These are in close agreement with the actual confirmation rates, showing that the photometric samples are well understood. A high confirmation rate (small

<table>
<thead>
<tr>
<th>FCJ^a</th>
<th>CORE^a</th>
<th>SUB^a</th>
</tr>
</thead>
<tbody>
<tr>
<td>α(J2000)</td>
<td>12:30:47.6</td>
<td>12:27:47.4</td>
</tr>
<tr>
<td>δ(J2000)</td>
<td>+12:38:32.4</td>
<td>+13:21:40.1</td>
</tr>
<tr>
<td>m(5007)b</td>
<td>27.0</td>
<td>27.2</td>
</tr>
<tr>
<td>N(&gt;27.2)b</td>
<td>18</td>
<td>34</td>
</tr>
<tr>
<td>N(b)</td>
<td>15</td>
<td>12</td>
</tr>
<tr>
<td>N(&lt;λ4959)b</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>N(&lt;m(5007)b</td>
<td>13</td>
<td>34</td>
</tr>
<tr>
<td>N(&lt;m(β)</td>
<td>11</td>
<td>11</td>
</tr>
<tr>
<td>Rate(&lt;m(b)</td>
<td>84%</td>
<td>32%</td>
</tr>
<tr>
<td>Predicted Rate(&lt;m(β</td>
<td>80%</td>
<td>17%</td>
</tr>
</tbody>
</table>


^bSymbols denote: limiting magnitude of photometric sample, m(5007); number of fibers allocated to objects with m < 27.2 and not in bad CCD regions, N(<27.2); number of detected PNe, Np; number of detected PNe with double lines, Np(λ4959); number of fibers allocated to objects brighter than min(27.2, m(5007)); Np(<m(5007)); number of detected such PNe, Np(<m(5007)); spectroscopic detection rate to m(5007); Rate(<m(5007) = Np(<m(5007))/Np(λ4959); corresponding rate predicted from photometry using simulations.

FIG. 1.— FLAMES spectra for 14 ICPNe observed in the FCJ (two left columns) and CORE fields. The spectrum in the lower right corner is a Lyα object, which shows a very broad line profile. The m(5007) magnitudes are marked on the individual frames.
contamination) can be achieved when the off-band image is sufficiently deep. See Aguerri et al. (2004) for further details.

4. ICPN LINE-OF-SIGHT VELOCITY DISTRIBUTIONS

With these data, we can now for the first time determine radial velocity distributions of ICPNe and use these to investigate the dynamical state of the Virgo cluster. Fig. 2 shows an image of the Virgo cluster core with the positions of our FLAMES pointings. The heliocentric radial velocity histograms obtained from the spectra in these fields are displayed in Fig. 3. Clearly the histograms for the three pointings are very different.

In the FCJ field, the velocity distribution of the PNe is not consistent with a single Gaussian with either the fitted velocity dispersion $\sigma_{\text{FCJ}} = 573$ km s$^{-1}$, or the more canonical Virgo $\sigma = 800$ km s$^{-1}$, based on a $\chi^2$-test. Instead, it is dominated by a narrow peak, with $v_p = 1276 \pm 71$ km s$^{-1}$ and $\sigma_p = 247 \pm 52$ km s$^{-1}$, which we identify with the halo of M87 below. In addition, there are 3 outliers at low velocity. All three are unusually bright, in the bright fall-off of the M87 PN luminosity function (PNLF), and they shift the FCJ luminosity function to a brighter cutoff (Arnaboldi et al. 2002). The ICL surface brightness associated with these 3 outliers, e.g. the likely true ICPNe in the FCJ field, is $\mu_B \approx 30.7$ mag arcsec$^{-2}$, if we use the conversion for M31 from Ciardullo et al. (1989), $\alpha_{1, B}$. This is comparable with the surface brightness measurements of Ferguson et al. (1998) and Durrell et al. (2002) from intracluster red giants in fields further away from M87.

The M87 peak of the FCJ velocity distribution contains 12 velocities, which are described well by a Gaussian according to KS and $\chi^2$ tests. Their luminosity function is consistent with the PNLF in the inner 4' of M87 (Ciardullo et al. 1998), with a KS probability $p_{\text{KS}} = 0.46$. The average velocity agrees with that of M87, $v_{\text{LOS}} = 1307$ km s$^{-1}$. The value of $\sigma_p$ is consistent with the stellar velocity dispersion profile extrapolated outwards from $\approx 150''$ in Figure 5 of Romanowsky & Kochanek (2001) and falls in the range spanned by their dynamical models for the M87 stars (the center of FCJ is 15.0' $\approx$ 65 kpc from M87, for an assumed M87 distance of 15 Mpc). To infer the surface brightness corresponding to the 12 PNe in the M87 peak, we again use $\alpha_{1, B}$ for M31, because of the colour gradient observed in the outer parts of M87 (Goudrooj et al. 1994). The resulting $\mu_B = 29.2$ mag arcsec$^{-2}$ falls on the average M87 surface brightness profile extrapolated from $\approx 400''$. $\mu_B$ and $\sigma_p$ are thus also consistent with the extrapolated dynamical model of Romanowsky & Kochanek (2001) for the M87 stars, in the distribution of dark matter inferred by them, which is also similar to that determined by Matsushita et al. (2002). By contrast, the available data and dynamical models show an approximately flat dispersion profile for the globular clusters in M87, at $\sigma_{\text{GC}} \approx 350$ km s$^{-1}$, corresponding to a shallower radial distribution. The main result from our measurement of $\sigma_p$ is that M87 has a stellar halo in approximate dynamical equilibrium out to at least 65 kpc.

In the CORE field, the distribution of ICPN line-of-sight (LOS) velocities is clearly broader than in the FCJ field and consistent with a Gaussian ($p_{\text{KS}} = 0.9$). It has $v_{\text{LOS}} = 1491 \pm 290$ km s$^{-1}$ and $\sigma_{\text{LOS}} = 1000 \pm 210$ km s$^{-1}$; the median is 1791 km s$^{-1}$. The CORE field is in a region of Virgo devoid of bright galaxies, but contains 7 dwarfs, and 3 low luminosity E/S near its S/W borders. None of the confirmed ICPNe lies within a circle of three times half the major axis diameter of any of these galaxies, and there are no correlations of their velocities with the velocities of the nearest galaxies where these are known. Thus in this field there is a clear IC stellar component.

The mean velocity of the ICPN in this field is similar to that of 25 Virgo dE and dS0 within 2'' of M87, $v_{\text{def.M87}} = 1436 \pm 108$ km s$^{-1}$ (Binggeli et al. 1987), and with that of 93 dE and dS0 Virgo members, $v_{\text{def.Virgo}} = 1139 \pm 67$ km s$^{-1}$ (Binggeli et al. 1993). However, the velocity dispersion of these galaxies is smaller, $\sigma_{\text{def.M87}} = 538 \pm 77$ km s$^{-1}$ and $\sigma_{\text{def.Virgo}} = 649 \pm 48$ km s$^{-1}$.

The inferred luminosity from the ICPNe in the CORE field is $1.8 \times 10^9 L_{B, \odot}$ (Aguerri et al. 2004). This is about
three times the luminosity of all dwarf galaxies in this field, 5.3 × 10^8 L_☉, but an order of magnitude less than the luminosities of the three low-luminosity E/S galaxies near the field borders. Using the results of Nulsen & Böhringer (1995) and Matsushita et al. (2002), we estimate the mass of the M87 subcluster inside 310 kpc (the projected distance D of the CORE field from M87) as 4.2 × 10^13 M_☉, and compute a tidal parameter T for all these galaxies as the ratio of the mean mass density within D to the mean density of the galaxy. We find T = 0.01 – 0.06, independent of galaxy luminosity. Since T ∼ D^2, any of these galaxies whose orbit now comes closer to M87 than ∼ 60 kpc would be subject to severe tidal mass loss. Thus the ICPNe population in the CORE field could be debris from the tidal disruption of small galaxies on nearby orbits in the M87 halo. The relatively small number of ICPNe in the FCJ field at D = 65 kpc could then mean that most of the tidally disrupted galaxies did not orbit as deep into M87.

In the SUB field the velocity distribution from FLAMES spectra is again different from CORE and FCJ. The KS test gives low probabilities, p_KS = 0.13 and p_KS = 0.03, that the SUB histogram could be drawn from the velocity histogram in the CORE field or the Gaussian fitted to this, respectively. Instead, the SUB histogram of LOS velocities shows substructures that are highly correlated with the systemic velocities of M86, M84 and NGC 4388. The association with the three galaxies is strengthened when we plot the LOS velocities of 4 HII regions (see Gerhard et al. 2002) detected with FLAMES in this pointing. The highest peak in the distribution coincides with M84, and even more so when we add the LOS velocities obtained previously at the TNG (Arnaboldi et al. 2003). The 10 TNG velocities (2 velocities were measured in addition to the Arnaboldi et al. (2003) sample) give \( \bar{v}_{\text{M84}} = 1079 ± 103 \, \text{km s}^{-1} \) and \( \sigma_{\text{M84}} = 325 ± 75 \, \text{km s}^{-1} \) within a square of 4R_e × 4R_e of the M84 center. The 8 FLAMES velocities in the M84 subpeak give \( \bar{v}_{\text{M84}} = 891 ± 74 \, \text{km s}^{-1} \) and \( \sigma_{\text{M84}} = 208 ± 54 \, \text{km s}^{-1} \), going out to larger radii. Note that this includes three over-luminous PNe not attributed to M84 previously. The combined sample of 18 velocities gives \( \bar{v}_{\text{M84}} = 995 ± 69 \, \text{km s}^{-1} \) and \( \sigma_{\text{M84}} = 293 ± 50 \, \text{km s}^{-1} \). Most likely, all these PNe belong to a very extended envelope around M84 (see the deep image in Arnaboldi et al. 1996).

It is possible that the somewhat low velocity with respect to M84 may be a sign of tidal stripping by M86, or of a recent merger with a smaller galaxy. In the latter case, the over-luminous PNe might be due to a younger or a more metal-poor population (Dopita et al. 1992).

5. CONCLUSIONS

We have presented the first measurements of the velocity distribution of ICPNe in three fields of the Virgo cluster. Overall, these velocity measurements confirm the view that Virgo is a highly non-uniform and unrelaxed galaxy cluster, consisting of several subunits that have not yet have had time to come to equilibrium in a common gravitational potential.

A well-mixed IC stellar population is seen clearly only in the CORE field, in the outer parts of the M87 subcluster. Here the velocity distribution is consistent with a single cluster Gaussian, and the ICPNe might well have their origin in the tidal effects of the halo of this subcluster on its galaxy population. In the SUB field near M84 and M86, the ICPNe do not appear virialized; their velocities are highly correlated with those of the large galaxies in the field. In fact, there are regions in Virgo where no ICPNe are found (the LPC field of Aguerri et al. 2004).

The measurements have also shown that M87 has a very extended envelope in approximate dynamical equilibrium, reaching out to at least 65 kpc. The cluster ICPN population in our FCJ field has density comparable with that in other fields further out, indicating a shallow ICL density distribution.

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