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Diffuse light in clusters of galaxies

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In galaxy clusters a diffuse intracluster stellar component has been detected from deep imaging and observations of individual intracluster stars, and recently some progress has been made in the study of intracluster starlight on several fronts.

Individual intracluster stars have been discovered in the Virgo cluster, and thank to innovative spectroscopic techniques planetary nebulae were detected in the Coma cluster. These intracluster stars give the promise of studying in detail the kinematics, metallicity and age of the intracluster stellar population in nearby galaxy clusters. Furthermore, intracluster light (ICL) is also potentially of great interest for studies of galaxy and galaxy cluster evolution. The dynamical evolution of cluster galaxies involves complex and imperfectly understood processes such as galactic encounters, cluster accretion, and tidal stripping. The properties of the ICL may also be sensitive to the distribution of dark matter in cluster galaxies, as simulations have shown that the structure of dark matter halos in galaxies plays a central role in the formation and evolution of tidal debris.

Current investigations aim at understanding about the origin of this diffuse stellar component, and the details of the cluster formation and evolution.

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1. Properties of diffuse light in clusters of galaxies

The first studies date back to the work of Zwicky (1951) on the luminosity function of galaxies in the Coma cluster. In his work, Zwicky pointed out that vast and irregular *swarms of stars* existed in the spaces between the standard galaxies in Coma, and commented whether they could be incorporated into the distribution function of known galaxy types. Zwicky's efforts were then followed by photographic surveys for diffuse light in Coma and other rich clusters in the 1970s; in the 1990s, CCD photometry provided the first accurate measurements in Coma, as described by Bernstein et al. (1995).

Two kind of problems affect these experiments: (a) the typical surface brightness of intracluster light (ICL) is less than 1% of the dark sky brightness, and (b) it is difficult to disentangle between diffuse light associated with the halo of the cD galaxy at the cluster center and the diffuse light component.

Since 1995, wide-field cameras equipped with a CCD mosaic allow accurate measurements of diffuse light in the Abell clusters. This stellar component is traced by tails, arcs and/or plumes with typical $\mu_B = 27.8$ mag arcsec^{-2}, very narrow ($\sim$ 2kpc) and extended ($\sim$ 100 kpc) in Coma and Centaurus (Gregg & West 1998, Threntam & Mobasher 1998, Calcáneo-Roldán et al. 2000). In addition, different groups have measured the radial surface brightness profile of the extended cD halos out to very large cluster radii. These measurements were carried out for the Abell cluster 1651 (Gonzalez et al. 2000), Abell 1413 & MKW7 (Feldmeier et al. 2002), in four Abell type II-III (non-cD) clusters (Feldmeier et al. 2004b) and for the compact group HGC90 (White et al. 2003).

The relationship between the total amount and spatial distribution of the ICL, and the relative clusters were investigated in recent papers. Lin & Mohr (2004) studied the near-infrared K-band properties of the brightest cluster galaxies (BCGs) in a sample of 93 X-ray galaxy clusters and groups, using data from the Two Micron All Sky Survey. They claim that a correlation exist between the cluster luminosity and mass; from this and a merger tree model for cluster formation, they estimate that the amount of ICL increases with cluster mass: in 10^{15} $M_\odot$ clusters more than 50% of total stellar mass is in ICL, making the role of ICL very important in the evolution and thermodynamic history of clusters. The cluster baryon fraction accounting for the ICL is then in good agreement with the value derived from cosmic microwave background observations.

An independent approach to the measurement of ICL in moderate $z = 0.2 - 0.3$ clusters has been carried out by Zibetti et al. (2005); they performed surface photometry (g, r and i bands) on stacked images of the clusters, after rescaling them to the same metric size and masking out resolved sources. They studied the spatial distribution and color of the ICL in 683 clusters of galaxies between z=0.2 and 0.3, selected from approx 1500 deg^2 of the SDSS-DR1. The average surface brightness profile of the ICL was detected out to 700 kpc, where it is less than 1/10,000 of the mean surface brightness of the dark night sky. The ICL appears as a clear surface brightness excess with respect to an inner $R^{1/4}$ profile which characterizes the mean profile of the brightest cluster galaxy (BCG). The surface brightness of the ICL ranges from 27.5 mag arcsec^{-2} at 100 kpc to roughly 32 at 700 kpc in the observed r-band. Zibetti et al. (2005) find that, on average, the ICL contributes only a small fraction of the total optical emission in a cluster (10.9 ± 5.0% within 500 kpc), while the BCG itself contributes a further 21.9%. Furthermore the radial distribution of the

ICL is more centrally concentrated than that of the cluster galaxies.

All these independent measurements place the lower limit to the fraction of diffuse light in clusters with respect to the amount of light in individual galaxies to 10% − 20%.

The ICL clearly plays a role in the chemical enrichment history of the intracluster medium (ICM). In contrast to scenarios in which all the metals originate in cluster galaxies and are then transported into the ICM, ICL enrich the ICM in situ, thereby contributing 100% of their supernovae ejecta directly into the ICM (Zaritsky et al. 2004). The ICL also makes it easier to produce the “iron excess” found in the central regions of cool-core clusters (Lin & Mohr 2004).

The presence of a diffuse stellar component in clusters is relevant also for the discussion of the baryonic mass in clusters (Fukugita et al. 1998) and the efficiency of star formation (Balogh et al. 2001).

1.1 Individual intracluster stars

An alternative method for probing ICL is through the direct detection and measurements of the stars themselves.

The detection of intergalactic supernovae was first reported by Smith (1981): a SN1a was observed in the Virgo cluster, in the region between M86 and M84. In 2003, Gam-Yam et al. observed two SN1a in Abell 403 ($z = 0.10$) and in Abell 2122/4 ($z = 0.066$) . Both events appear projected on the halos of the central cDs, since no other obvious hosts are present, but these stars have a substantial velocity offset (750 - 2000 km s^{-1}) from the cD systemic velocity suggesting that they are not bound to it, but are free-flying in the cluster potential. Gam-Yam and collaborators estimate that 20% of the SN1a parent stellar population in clusters is intergalactic (Gam-Yam et al. 2003). Neill et al. (2004) carried out a survey for novae in the Fornax cluster. They discovered six nova candidates in six distinct epochs spanning eleven years from 1993 to 2004. Their estimate to the lower limit to the ICL in the Fornax cluster is 16%.

In 1995, West and collaborators argued that a population of intergalactic globular clusters (IGCs) exists in all clusters and are concentrated towards the center (West et al. 1995). High values of the GC frequency (S_N) in cDs is then the results of the accretion of a number of IGCs. Independent evidence was acquired by Coté et al. (2001) around M87, where they concluded that the metal poor GCs were not formed in situ, but stripped from the Virgo cluster dwarfs. In the cluster Abell 1185, Jordàn et al. (2003) searched for a population of IGCs, in a field centered on the peak of the cluster's X-ray emission, which contains no bright galaxies. An excess of point like sources is found with respect to HDF North, which Jordàn and collaborators associate with a population of IGCs. Bassino et al. (2003) also reported on the discovery of IGC candidates in the Fornax cluster.

In the intracluster (IC) regions, an additional kind of stellar cluster is found. Drinkwater et al. (2003) discovered Ultra-compact dwarfs (UDCs) in the Fornax cluster; they are nucleated dwarf galaxies whose outer envelopes were stripped by interactions with the cD, at the cluster center.

Direct observations of stars in Virgo IC fields were carried out by Ferguson, Tanvir & von Hippel in 1998 with HST. The presence of intracluster red giant stars (IRGBs) was inferred from the excess of red number counts in a Virgo IC field with respect to the HDF North. By comparing the I-band star counts into two Virgo cluster fields with similar observations for a metal-poor nucleated dwarf elliptical, Durrell et al. (2002) found an offset between the RGB tip of the IRGBs and that in the dwarf. Their interpretation is that the bulk of the IRGBs are moderately metal rich $(-0.8 < [Fe/H] < -0.2)$. The surface brightness associated with the IRGB counts is $\mu_I = 27.9$ mag arcsec^{-2}, and it amounts to 15% of the Virgo cluster galaxy I band luminosity. The discovery of an isolated compact HII region in the Virgo cluster (Gerhard et al. 2002) has shown that some star-formation activity can indeed take place in the outskirts of galaxy halos if not already in Virgo IC space.

2. Intracluster light in cosmological simulations

The presence of diffuse `intracluster light' in galaxy groups and clusters is now well established. The fraction of stars contained in this space-filling component seems to increase strongly with the density of the environment: from loose groups ($<$ 2%, Castro-Rodriguez et al. 2003; Durrell et al. 2003) to Virgo-like ($<$ 10%; Feldmeier et al. 2003; Arnaboldi et al. 2003: Aguerri et al. 2005) or Abell type II-III (non-cD) galaxy clusters ($\sim$ 10%; Feldmeier et al. 2004b), and rich clusters ($\sim$ 20% or higher; Gonzalez et al. 2000, Feldmeier et al. 2002; Gal-Yam et al. 2003). This correlation may represent an important clue for understanding the mechanisms that produce ICL and drive its evolution in the cluster environment.

Cosmological simulations of structure formation facilitate studies of the diffuse light and its expected properties. Dubinski (1998) constructed compound models of disk galaxies and placed them into a partially evolved simulation of cluster formation, allowing an evolutionary study of the dark matter and stellar components independently. Using an empirical method to identify stellar tracer particles in high-resolution cold dark matter (CDM) simulations, Napolitano et al. (2003) studied a Virgo-like cluster, finding evidence of a young dynamical age of the intracluster component. The main limitation in these approaches is the restriction to collisionless dynamics.

Murante et al. (2004) analyzed for the first time the ICL formed in a cosmological hydrodynamical simulation including a self-consistent model for star formation. In this method, no assumptions about the structural properties of the forming galaxies need to be made, and the gradual formation process of the stars, as well as their subsequent dynamical evolution in the non-linearly evolving gravitational potential can be seen as a direct consequence of the ΛCDM initial conditions. Murante et al. (2004) identified 117 clusters in a large volume of $192^3\,h^{-3}$Mpc^3, and analyze the correlations of properties of diffuse light with, e.g., cluster mass and X-ray temperatures. These predictions can be tested against known properties of cD halos and used to plan observational tests to understand the physical properties of ICL.

The presence of the IC component is evident when the whole distribution of stars in the simulated clusters is analyzed in a way similar to Schombert's (1986) photometry of brightest cluster galaxies (BCGs). Galaxies at the centers of Murante et al. (2004) simulated clusters have surface-brightness profiles which turn strongly upward in a $(\mu, R^{1/\alpha})$ plot. This light excess can be explained as IC stars orbiting in the cluster potential. Integrating its density distribution along the LOS, the slopes from our simulations are in agreement with those observed for the surface brightness profiles of the diffuse light in nearby clusters. In the Coma cluster, Bernstein et al. (1995) parameterize the surface brightness as r^{β} and find that the diffuse light is best fit by $\beta = -1.3 \pm 0.1$. In the Fornax cluster, the surface brightness profile of the cD envelope of NGC 1399 follows a power law of the form $\propto r^{\beta}$ with $\beta = -1.5$.

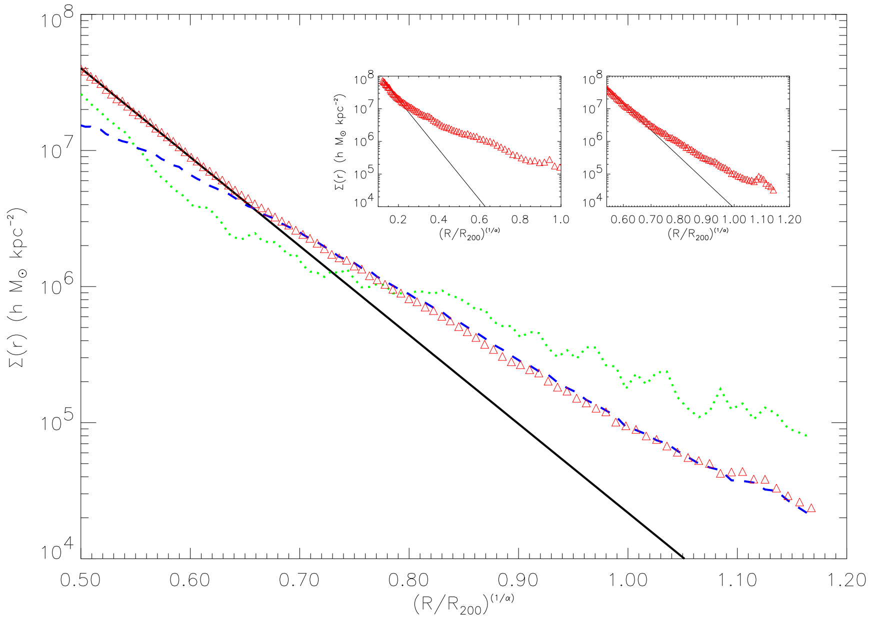

Figure 1: Schombert–like analysis on the *stacked* 2D radial density profile (BCG + ICL) of clusters in the Murante et al (2004) simulation (triangles). The light excess is evident at large cluster radii. The solid line shows the function $\log\Sigma(r) = \log\Sigma_e - 3.33[(r/r_e)^{1/\alpha} - 1]$, with best–fit parameters $\log\Sigma_e = 20.80$, $r_e = 0.005$, $\alpha = 3.66$ to the BCG inner stellar light. Also shown are the averaged 2D density profile of stars in galaxies (dotted line) and in the field (dashed line). In the inserts, the results are shown from the same analysis for the most luminous clusters with $T > 4$ keV (left panel), and for less luminous ones with $0 < T < 2$ keV (right panel). The resulting best–fit parameters are respectively $\log\Sigma_e = 16.47$, $r_e = 0.11$, $\alpha = 1.24$ and $\log\Sigma_e = 23.11$, $r_e = 0.00076$, $\alpha = 4.37$. In the main plot and in the inserts the unit $(R/R_{200})^{1/\alpha}$ refers to the α values given by each Sersic profile. From Murante et al. (2004).

At large cluster radii, the surface brightness profile of the ICL appears more centrally concentrated than the surface brightness profile of cluster galaxies (see Fig. 1) as seen in the ICL surface brightness profiles measured by Zibetti et al. (2005) for the SDSS clusters.. From the simulations carried out by Murante et al. (2004), they also obtained the redshifts z_{form} at which the stars formed: those in the IC component have a z_{form} distribution which differs from that in cluster galaxies, see Fig. 2. The "unbound" stars are formed earlier than the stars in galaxies. The prediction for an old stars' age in the diffuse component agrees with the HST observation of the IRGB stars in the Virgo IC field, e.g. $t > 2$Gyr (Durrell et al. 2002), and points toward the early tidal interactions as the preferred formation process for the ICL. The different age and spatial distribution of the stars in the diffuse component indicate that it is a stellar population that is not a random sampling of the stellar populations in cluster galaxies.

Murante et al. (2004) studied the correlation between the fraction of stellar mass in the diffuse component and the clusters' total mass in stars, based on their statistical sample of 117 clusters. This fraction is ~ 0.1 for cluster masses $M > 10^{14}h^{-1}M_{\odot}$ and it increases with cluster mass: the more massive clusters have the largest fraction of diffuse light (Fig. 2). For $M \sim 10^{15}h^{-1}M_{\odot}$,

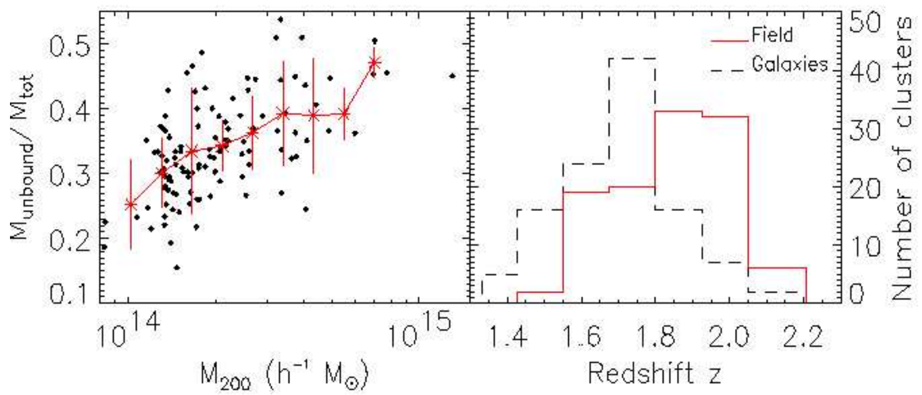

Figure 2: Left: Fraction of stellar mass in diffuse light vs. cluster mass. Dots are for clusters in the simulated volume; asterisks show the average values of this fraction in 9 mass bins with error-bars. Right panel: histograms of clusters over mean formation redshift, of their respective bound (dashed) and IC star particles (solid line). Mean formation redshifts are evaluated for each cluster as the average on the formation redshift of each star particle. From Murante et al. (2004).

simulations predict as many stars in the diffuse component as in cluster galaxies, in agreement with similar evaluations from Lin & Mohr (2004).

2.1 Dynamics of the ICL

In the currently favored hierarchical clustering scenario, fast encounters and tidal interactions within the cluster potential are the main players of the morphological evolution of galaxies in clusters. Fast encounters and tidal stirring cause a significant fraction of the stellar component in individual galaxies to be stripped and dispersed within the cluster in a few dynamical times. If the time-scale for significant phase-mixing is on the order of few cluster internal dynamical times, then a fraction of the ICL should still be located in long streams along the orbits of the parent galaxies. detections of substructures in phase space would be a clear sign of late infall and harassment as the origin of the ICL.

A high resolution simulation of a Virgo-like cluster in a ΛCDM cosmology was used to predict the velocity and the clustering properties of the diffuse stellar component in the intracluster region at the present epoch (Napolitano et al. 2003). The simulated cluster builds up hierarchically and tidal interactions between member galaxies and the cluster potential produce a diffuse stellar component free-flying in the intracluster medium. The simulations are able to predict the radial velocity distribution expected in spectroscopic follow-up surveys: they find that at $z = 0$ the intracluster stellar light is mostly dynamically unmixed and clustered in structures on scales of about 50 kpc at a radius of 400 – 500 kpc from the cluster center.

Willman et al. (2004) and Sommer-Larsen et al. (2004) have studied the dynamics of the ICL in cosmological hydrodynamical simulations. Willman et al. (2004) finds that the ICL show significant substructure in velocity space, tracing separate streams of stripped IC stars. Evidence is given that despite an un-relaxed distribution, IC stars are useful mass tracers, when several fields

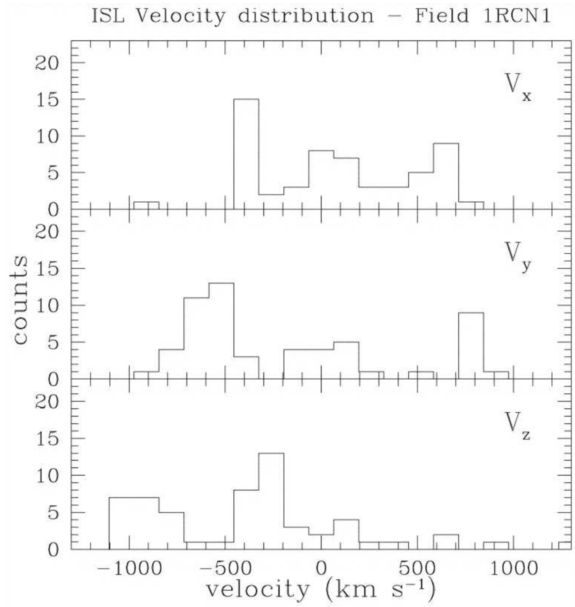

Figure 3: Velocity distribution of a simulated ICPNe sample in a N-body simulation of a Virgo-like cluster. From Napolitano et al. (2003).

at a range of radii have measured line-of-sight (LOS) velocities. According to Sommer-Larsen et al. (2004) IC stars are colder than cluster galaxies. This is to be expected given that they are more centrally concentrated than cluster galaxies (Murante et al. 2004) and are both in equilibrium with the same cluster potential.

3. Planetary Nebulae as tracers of cluster evolution

Intracluster planetary nebulae (ICPNe) have several unique features that make them ideal for probing the ICL. The diffuse envelope of a PN re-emits 15% of the UV light of the central star in one bright optical emission line, the green [OIII]λ5007 Å line. PNe can therefore readily be detected in external galaxies out to distances of 25 Mpc and their velocities can be determined from moderate resolution $(\lambda/\Delta\lambda \sim 5000)$ spectra: this enables kinematical studies of the IC stellar population.

PNe trace stellar luminosity and therefore provide an estimate of the total ICL. Also, through the [OIII] λ5007 Å planetary nebulae luminosity function (PNLF), PNe are good distance indicators, and the observed shape of the PNLF provides information on the line of sight distribution of the IC starlight. Therefore ICPNe are useful tracers to study the spatial distribution, kinematics, and metallicity of the diffuse stellar population in nearby clusters.

3.1 Current narrow band imaging surveys

Several groups (Arnaboldi et al. 2002, 2003; Feldmeier et al. 2003, 2004a; Aguerri et al. 2005) have embarked on narrow-band [OIII] imaging surveys in the Virgo cluster, with the aim of determining the radial density profile of the diffuse light, and gaining information on the velocity

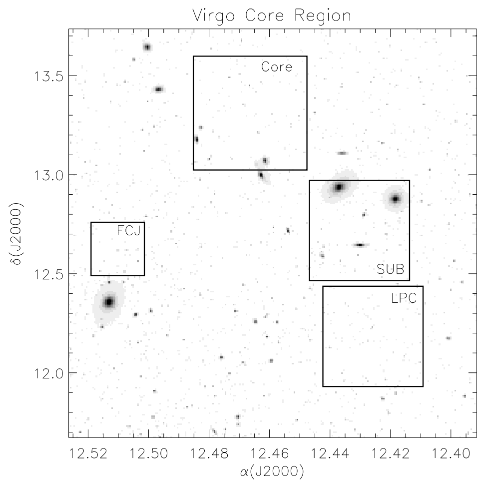

Figure 4: Aguerri et al. (2005) surveyed fields in the Virgo cluster core.

distribution via subsequent spectroscopic observations of these samples. Given the use of the PNLF as distance indicators, one also derives valuable information on the 3D shape of the Virgo cluster from these ICPN samples. Wide-field mosaic cameras, such as the WFI on the ESO MPG 2.2m telescope and the Suprime Cam on the Subaru 8.2m, allow us to identify the ICPNe associated with the extended ICL (Arnaboldi et al. 2002, 2003; Okamura et al. 2002). These surveys require the use of data reduction techniques suited for mosaic images, and also the development and refining of selection criteria based on color-magnitude diagrams produced with SExtractor.

The data analyzed by Aguerri et al. (2005) constitute a sizeable sample of ICPNe in the Virgo core region, constructed homogeneously and according to rigorous selection criteria; a layout of the pointings is shown in Fig. 4. From the study of four wide-fields they conclude that the mean surface luminosity and brightness in the Virgo core region are 2.7×10^6 $L_{B\odot}$ arcmin^{-2}, $\mu_B =$ 29.1 mag arcsec^{-2} respectively. These values are in good agreement with those obtained from excess red giant counts in two deep HST images in the Virgo core (Durrell et al. 2002). There exists significant field-to-field variations in the amount of ICL in this region, with some empty fields, some fields dominated by extended Virgo galaxy halos and some fields dominated by ICPNe. The authors argue that when they compare the luminosity of the ICL at the different positions of their fields with the Virgo galaxies, further uncertainties are introduced in the estimates, because luminosities from Virgo galaxies depend very much on the location and field size surveyed in the Virgo cluster. Similar measured surface brightnesses for the ICL may therefore results in higher or smaller fraction depending on the adopted normalization relative to the Virgo galaxy light.

4. Spectroscopic follow-up

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 un-relaxed, showing significant substructure in its spatial and velocity distributions in clusters similar to Virgo.

The spectroscopic follow-up with FLAMES of the ICPN candidates selected from three survey fields in the Virgo cluster core was carried out by Arnaboldi et al. (2004). Radial velocities of 40 ICPNe in the Virgo cluster were obtained with the new multi-fiber FLAMES spectrograph on UT2 at VLT. The spectra were taken for a homogeneously selected sample of ICPNe, previously identified in three ~ 0.25 deg^2 fields in the Virgo cluster core from Aguerri et al. (2005). For the first time, the λ 4959 Å line of the [OIII] doublet is seen in a large fraction (40%) of ICPNe spectra, and a large fraction of the photometric candidates with m(5007) < 27.2 is spectroscopically confirmed.

4.1 The line-of-sight velocity distributions of ICPNe in the Virgo cluster core.

With these data, Arnaboldi et al. (2004) were able for the first time to determine radial velocity distributions of ICPNe and use these to investigate the dynamical state of the Virgo cluster. Fig. 5 shows the radial velocity distributions obtained from the FLAMES spectra in FCJ, CORE and SUB fields, as they are labelled in Fig. 4. Clearly the velocity distribution histograms for the three pointings are very different.

In the FCJ field, the ICPNe distribution is dominated by the halo of M87. There are 3 additional outliers, 2 at low velocity, which are also in the brightest PNLF bin, and therefore may be in front of the cluster. The surface brightness of the ICL associated with the 3 outliers, e.g. the ICPNe in the FCJ field, amounts to $\mu_B \simeq 30.63$ mag arcsec^{-2}, in agreement with the surface brightness measurements of Ferguson et al. (1998) and Durrell et al. (2002) of the IRGB stars.

The M87 peak of the FCJ velocity distribution contains 12 velocities with $\bar{v}_p = 1276 \pm 71$ km s^{-1} and $\sigma_p = 247 \pm 52$ km s^{-1}. The average velocity is consistent with that of M87, $v_{sys} = 1258$ km s^{-1}. The distance of the center of the FCJ field from the center of M87 is $15.'0 \simeq 65$ kpc for an assumed M87 distance of 15 Mpc. The value of σ_p is very consistent with the stellar velocity dispersion profile extrapolated outwards from $\simeq 150''$ in Figure 5 of Romanowsky & Kochanek (2001) and falls in the range spanned by their dynamical models for the M87 stars. The main result from our measurement of σ_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 LOS velocities is clearly broader than in the FCJ field. It has $\bar{v}_C = 1491 \pm 290$ km s^{-1} and $\sigma_C = 1000 \pm 210$ 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 true IC stellar component.

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

The inferred luminosity from the ICPNe in the CORE field is $1.8 \times 10^9 L_{B,\odot}$. This is about three times the luminosity of all dwarf galaxies in this field, $5.3 \times 10^8 L_{B,\odot}$, but an order of magnitude less than the luminosities of the three low-luminosity E/S galaxies near the field borders. Using the

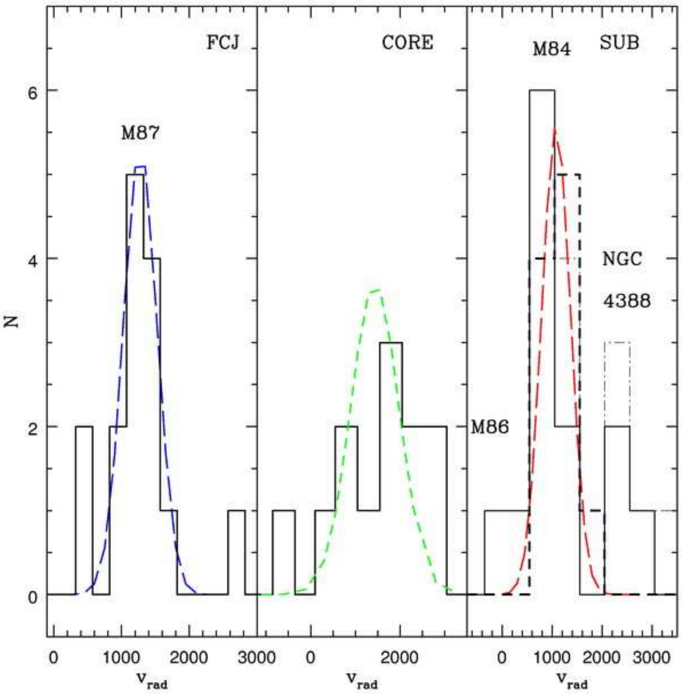

Figure 5: ICPN radial velocity distributions in the three pointings (FCJ, CORE, and SUB) from Aguerri et al. (2005). In FCJ panel, blue dashed line shows a Gaussian with $\bar{v}_{rad} = 1276$ km s^{-1} and $\sigma_{rad} = 247$ km s^{-1}. In CORE, green dashed line shows a Gaussian with $\bar{v}_{rad} = 1436$ km s^{-1} and $\sigma_{rad} = 538$ km s^{-1}, for VC galaxies dE and dS0 within 2° of M87 (from Binggeli et al. 1987). In SUB, dashed histogram shows radial velocities from TNG spectroscopic follow-up (Arnaboldi et al. 2003). Dashed red line shows a Gaussian with $\bar{v}_{rad} = 1080$ km s^{-1} and $\sigma_{rad} = 286$ km s^{-1}. Dashed-dotted lines show the SUB-FLAMES spectra including those spectra for HII regions, which have radial velocities in M84 & NGC 4388 redshift ranges.

results of Nulsen & Böhringer (1995) and Matsushita et al. (2002), Arnaboldi et al. (2004) estimate the mass of the M87 subcluster inside 310 kpc (the projected distance D of the CORE field from M87) as $4.2 \times 10^{13} M_{\odot}$, and compute a tidal parameter T for all these galaxies as the ratio of the mean density within the CORE field to the mean density of the galaxy. They find $T = 0.01 - 0.06$, independent of galaxy luminosity. Since $T \sim D^{-2}$, any of these galaxies whose orbit *now* comes closer to M87 than ~ 60 kpc would be subject to severe tidal mass loss. Based on the evidence sofar, a tantalizing possibility is that the ICPN population in the CORE field could be debris from the tidal disruption of small galaxies on nearby orbits in the M87 halo.

In the SUB field the velocity distribution from FLAMES spectra is again different from CORE and FCJ. The histogram of the LOS velocities shows substructures related to M86, M84 and NGC 4388, respectively. 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 substructures in this distribution are highly correlated with the galaxy systemic velocities. 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 give $\bar{v}_{\rm M84} = 1079 \pm 103$ km s^{-1} and $\sigma_{\rm M84} = 325 \pm 75$ km s^{-1} within a square of $4R_e \times 4R_e$ of the M84 center. The 8 FLAMES velocities give $\bar{v}_{M84} = 891 \pm 74$ km s^{-1} and $\sigma_{M84} = 208 \pm 54$ km s^{-1}, going out to larger radii. Note that this includes the over-luminous PNe not attributed to M84 previously. The combined sample of 18 velocities gives $\bar{v}_{M84} = 996 \pm 69$ km s^{-1} and $\sigma_{M84} = 293 \pm 50$ km s^{-1}. Most likely, all these PNe belong to a very extended halo 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.

5. Future Developments

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 (Feldmeier et al. 2004a; Aguerri et al. 2005), substructures in velocity space still need to be investigated. The work by Arnaboldi et al. (2004) represents an example of the follow-up studies on the dynamics of the Virgo cluster based on current ICPN catalogues. These will give us the possibility of understanding how the several subunits came together to form the Virgo cluster as we observe it now.

Studies of galaxy and galaxy cluster evolution indicate that the density of the environment has important implications on galaxy evolution. The Virgo cluster is a relatively low density, loose cluster so it would be of importance to study the properties of ICL in denser, more compact environments, like for example the Coma cluster. Detecting the faint emission of single planetary nebulae stars in the Coma cluster which is 5 times more distant than Virgo, represents an observational challenge in itself.

The observations by Gerhard et al. (2005) have successfully detected the [OIII] 5007Å emission by ICPN in the Coma cluster with the Multi-Slit Imaging Spectroscopy (MSIS) technique. This approach is similar to the one used to search for Lyα emitting galaxies at very high redshift, and it precedes much additional research to come.

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References

[1]Aguerri, J.A.L., et al. 2005, AJ, in press

[2]Arnaboldi, M. et al. 2004, ApJL, 614, 333

[3]Arnaboldi, M. et al. 2003, AJ, 125, 514

[4]Arnaboldi, M. et al. 2002, AJ, 123, 760

[5]Arnaboldi, M. et al. 1996, ApJ, 472, 145

[6]Balogh, M.L. et al. 2001, MNRAS, 326, 1228

[7]Bassino, L.P., et al. 2003, A&A, 399, 489

[8]Bernstein, G.M., et al. 1995, AJ, 110, 1507

[9]Binggeli, B., Popescu, C. C., & Tammann, G. A. 1993, A&A, 98, 275

[10]Binggeli, B., Tammann, G.A., & Sandage, A. 1987, AJ, 94, 251

[11]Calcáneo-Roldán, C., et al. 2000, MNRAS, 314, 324

[12]Castro-Rodriguez, N., et al. 2003, A&A, 405, 803

[13]Coté, P., et al. 2001, ApJ, 559, 828

[14]Drinkwater, M.J., et al. 2003, Nature, 423, 519

[15]Dubinski, J. 1998, ApJ, 502, 141

[16]Durrell, P.R., et al. 2003, ApJ, 582, 170

[17]Durrell, P.R., et al. 2002, ApJ, 570, 119

[18]Feldmeier, J.J., et al. 2004a, ApJ, 615, 196

[19]Feldmeier, J.J., et al. 2004b, ApJ, 609, 617

[20]Feldmeier, J.J., et al. 2003, ApJS, 145, 65

[21]Feldmeier, J.J., et al. 2002, ApJ, 575, 779

[22]Ferguson, H.C., Tanvir, N.R., & von Hippel, T. 1998, Nature, 391, 461

[23]Fukugita, M. et al. 1998, ApJ, 503, 518

[24]Gal-Yam, A.H. et al. 2000, ApJ, 536, 561

[25]Gerhard, O. et al. 2005, ApJL, in press

[26]Gerhard, O., Arnaboldi, M., Freeman, K.C., Okamura, S. 2002, ApJL, 580, 121

[27]Gonzalez, A. H., Zabludoff, A. I., Zaritsky, D., & Dalcanton, J. J. 2000, ApJ, 536, 561

[28]Gregg, M.D., & West, M.J. 1998, Nature, 396, 549

[29]Lin, Y., & Mohr, J.J. 2004, ApJL, 617, 879

[30]Jordán, A., et al. 2003, AJ, 125, 1642

[31]Matsushita, K., Belsole, E., Finoguenov, A., Böhringer, H. 2002, A&A, 386, 77

[32]Murante, G., et al. 2004, ApJL, 607, 83

[33]Napolitano, N.R., et al. 2003, ApJ, 594, 172

[34]Neill, J.D., Shara, M.M., Oegerle, W.R. 2004, ApJ, in press (astro-ph/0409265)

[35]Nulsen, P. E. J., & Böhringer, H. 1995, MNRAS, 274, 1093

[36]Okamura, S., et al. 2002, PASJ, 54, 883

[37]Romanowsky, A. J., & Kochanek, C. S. 2001, ApJ, 553, 722

[38]Schombert, J. 1986, ApJS, 60, 603

[39]Smith, H.A. 1981, AJ, 86, 998

[40]Sommer-Larsen, J., Romeo, A.D. & Portinari, L. 2004, MNRAS, submitted (astro-ph/0403282)

[41]Trentham, N., & Mobasher, B. 1998, MNRAS, 293, 53

[42]West, M.J., et al. 1995, ApJL, 453, 77

[43]White, P.M., et al. 2003, ApJ, 585, 739

[44]Willman, B., et al. 2004, MNRAS, 355, 159

[45]Zaritsky, D., Gonzalez, A. H., Zabludoff, A. I. 2004, ApJL, 613, 93

[46]Zibetti, S., White, S.D.M., Schneider, D., Brinkmann, J. 2005, MNRAS, in press (astro-ph/0501194)

[47]Zwicky, F. 1951, PASP, 63, 61