Part 1. Census
The Intracluster Medium

Intracluster Stellar Population

Magda Arnaboldi

INAF, Astronomical Observatory of Turin, Strada Osservatorio 20, 10025 Pino Torinese, Italy

Abstract. I shall review the latest results for the presence of diffuse light in nearby clusters, and the evidence of ongoing star formation in an intracluster Virgo field. I shall discuss how intracluster planetary nebulae (ICPN) can be used as excellent tracers of the diffuse stellar population in nearby clusters. Their number density distribution, density profile and radial velocity distribution provide observational constraints to models for cluster formation and evolution. The preliminary comparison of the available ICPN samples with high resolution N-body models of a Virgo-like cluster in a Lambda CDM cosmology supports "harassment" as the most likely mechanism for the origin of diffuse stellar light in clusters.

1. Introduction: Discovery of diffuse light in clusters

Stars are usually observed to form in galaxies (disks, dwarfs and starbursts). In nearby galaxy clusters, however, a diffuse intracluster stellar component has been detected from deep imaging and observations of individual intracluster stars.

Intracluster light (ICL) is 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. Various studies have suggested that between 10% and 50% of a cluster's total luminosity may be contained in the ICL, with a strong dependence on the dynamical state of the cluster. 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 DM halos in galaxies plays a central role in the formation and evolution of tidal debris (Dubinski et al. 1999).

Recently some progress has been made in the study of intracluster star light on several fronts. Individual intracluster stars, including planetary nebulae detected from the ground and red giants detected using HST, have been discovered in the Virgo cluster. These intracluster (IC) stars give the promise of studying in detail the kinematics, metallicity and age of the intracluster stellar population in nearby galaxy clusters and thereby learning about the origin of this diffuse stellar component, and the details of the cluster origin.

2. Intracluster light: an historical perspective

The first studies on this subject 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 typical 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 have allowed 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) and for the compact group HGC90 (White et al. 2003). Quoting from Uson et al. (1991), " ...*whether this diffuse light is called the cD envelope or diffuse intergalactic light is a matter of semantics: it is a diffuse component which is distributed with elliptical symmetry about the center of the cluster potential*". 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 20%.

2.1. Direct detection of IC 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. (2003) 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, 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.

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 result 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 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 $\mu_L = 27.9$ mag arcsec^{-2}, and it amounts to 15% of the Virgo cluster galaxy I band luminosity.

Are these stars tidally stripped from galaxies during the early phases of cluster collapse, or are they removed gradually over time via "galaxy harassment"? Do all of these stars have parent galaxies or do they form *in situ*? The recent 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.

3.   Intracluster Planetary Nebulae as tracers of cluster evolution

Intracluster planetary nebulae (ICPNe) have several unique features that make them ideal for probing 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 IC light. 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.

ICPNe are useful tracers to study the spatial distribution, kinematics, and metallicity of the diffuse stellar population in nearby clusters. Different cluster formation mechanisms predict different spatial distributions and velocity distributions for the IC stars. If most of the IC light originates in the initial cluster collapse (Merritt 1984), its distribution and kinematics should follow closely that of galaxies in the cluster. On the other hand, if the IC light builds slowly with time because of "galaxy harassment" (Moore et al. 1996) and "tidal stirring" (Mayer et al. 2001) , then a fraction of IC light may still be located in long

streams along the orbits of the parent galaxies, and dynamically unmixed structures should be easily visible in phase space, see the analog in the Milky way (Helmi 2001).
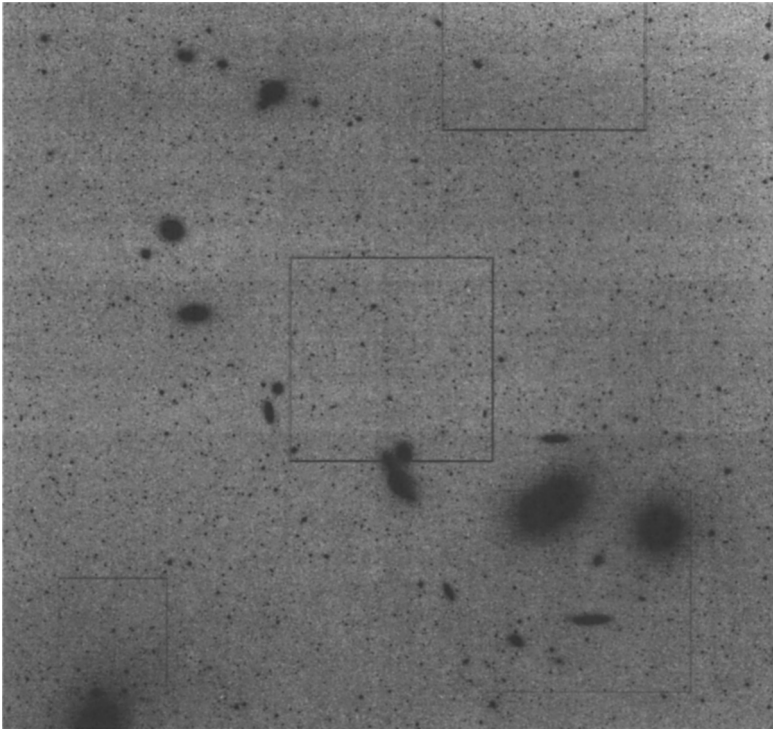

Figure 1.   Surveyed fields in the Virgo cluster: the two upper fields were obtained at the ESO MPI 2.2m telescope, and the lower-right field with the Suprime Cam at the 8.2m Subaru telescope. The lower-left field is from Feldmeier et al. (1998) and was used to test the selection criteria on the spectroscopically confirmed ICPNe in Arnaboldi et al. (2002). Several more fields need to be surveyed to determine the large scale surface density distribution of the ICL in the Virgo cluster.

3.1.   Narrow-band wide-field surveys

Several groups (Arnaboldi et al. 2002, 2003; Feldmeier et al. 1998, 2003; Okamura et al. 2002) have embarked on a narrow-band [OIII] imaging survey in the Virgo cluster, with the aim of determining the radial density profile of the diffuse light, and gaining information on the velocity distribution via subsequent spectroscopic observations of the obtained samples. Given the use of the PNLF as distance indicators, one also acquires valuable information on the 3D shape of the Virgo cluster from these ICPN samples, see also Feldmeier et al. (1998).

Wide-field mosaic cameras, such as the WFI on the ESO MPI 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): a layout of the fields' position on the DSS image of the Virgo core region are shown on Figure 1. 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 (CMD) produced with SExtractor.

In Arnaboldi et al. (2002), the on-band/off-band [OIII] imaging technique which has been used for PNe identification in Virgo and Fornax ellipticals has been translated into the following selection criteria for the most reliable detection of ICPN candidates:

1. the source should be unresolved;

2. the source should have an emission line $EW > 100$ Å. This is evaluated by measuring the ([OIII] - V) color between a detected object in the on-band [OIII] image and the signal in the corresponding position in the off-band V image. The EW criterion corresponds to a filter-dependent color excess relative to field stars;

3. there should be no source detected in the V-band image at the position of the detected [OIII] source.

The requirement on EW greatly reduces the contamination from [OII] starburst emitters at $z \sim 0.35$. The color selection must take into account the photometric errors in the final on-image, via simulation of unresolved sources.
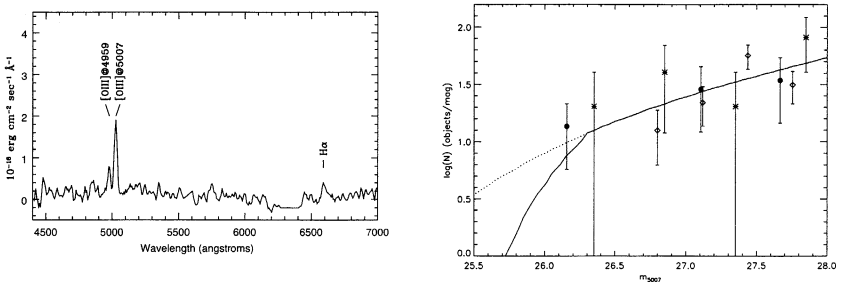

Figure 2.   Left panel − Spectrum of the confirmed intracluster PN in the Virgo cluster. The [OIII] doublet and the Hα emission are visible in this high S/N spectrum. Right panel − The solid line shows the expected luminosity function (LF) of the field Lyα population at redshift $z = 3.1$ for objects with $V < 24.73$. The faint dotted line shows the expected Lyα LF without any magnitude constraints in the V band. Asterisks indicate the LF of spectroscopically confirmed Lyα emitters from Kudritzki et al. (2000). Filled dots and diamonds show the LF of Lyα emitters in two other blank-field surveys. These are all consistent; from Castro-Rodriguez et al. (2003).

4. Spectroscopic confirmation and first results

Since the early spectroscopic detections of ICPNe by Arnaboldi et al. (1996), the spectroscopic follow-up of the Feldmeier et al. (1998) Virgo ICPN sample, carried out by Freeman et al. (2000) using 2dF at the Anglo-Australian Telescope, showed that most of the emission line sources in this sample are indeed ICPNe, because the combined spectrum of all the "sharp line" emitters clearly showed the [OIII] 4959/5007 Å doublet. In 2002, a high S/N spectrum for a single ICPN in the Virgo cluster, shown in Figure 2, was obtained for the first time at the VLT-UT4 with FORS2 by Arnaboldi et al. (2003). We conclude that the existence of ICPNe in the Virgo cluster is now beyond doubt.

Why then did the spectroscopic study by Kudritzki et al. (2000) find only background galaxies? The answer lies in examination of the luminosity function (LF) of their objects. The LF of the candidates studied by Kudritzki et al. (2000) follows closely the LF of field Lyα emitters at $z = 3.1$; see Figure 2.

One can compare the LF for the Lyα emitters with the LF for the spectroscopically confirmed ICPNe. These confirmed ICPNe are mostly brighter than the brightest of the Lyα emitters shown in Figure 2. The brightest of the emission line candidates studied by Kudritzki et al. (2000) is 0.5 mag fainter than the bright cutoff in the PNLF for M87, and 0.8 mag fainter than the bright cutoff for the spectroscopically confirmed ICPNe in the Virgo cluster. Most of the current ICPN candidates in Virgo are within 1 mag of the bright cutoff in the PNLF. This is the reason why Kudritzki et al. did not find ICPNe. Their sample was dominated by the Lyα emitters which are more abundant at fainter magnitudes. (See also Arnaboldi et al. 2002).

The bright cut-off of the LF for the Virgo ICPNe is about 0.3 mag brighter than for the PNe in individual Virgo galaxies. This is believed to be due to the elongated structure of the Virgo cluster, as previously found for the distribution of Virgo spiral galaxies using the Tully-Fisher relation.

What is the fraction of Lyα emitters in the first magnitude of the LF for the Virgo ICPN samples? When Arnaboldi et al. (2002) computed the fraction of Lyα emitters which can contaminate the ICPN candidate sample selected as outlined in Section 3.1, it amounts to about 15% of the observed sample. This estimate is supported by the empty field survey of Castro-Rodriguez et al. (2003).

5. Properties of the diffuse light in Virgo cluster

A primary goal is to estimate the fraction of light from intracluster stars in the surveyed region of the Virgo cluster. In our 0.25 deg^2 field at a distance of 1° from the cluster center, the ICPN sample indicates a total associated luminosity of $5.8 - 7.5 \times 10^9$ L$_{B,\odot}$, which corresponds to a surface luminosity of $0.33 - 0.57$ L$_{B,\odot}$ pc^{-2} or a surface brightness of $\mu_{B,*} = 28 - 27.7$ mag arcsec^{-2}. As discussed by Arnaboldi et al. (2002), over the range of radii probed by the survey fields, the luminosity surface density of galaxies in Virgo decreases by a factor of ~ 3, while that for the ICPNe is nearly constant. Therefore, from the data available so far, the ICPNe in Virgo are not centrally concentrated; however we need to investigate fields at larger radii to constrain the total amount of IC light.

One needs to compare the luminosity derived for the diffuse population with the luminous contribution from Virgo galaxies. If ICPNe are produced by phenomena acting locally, as the structure in the ICPN distribution shown in Okamura et al. (2002) seems to support, then the fraction of diffuse light with respect to the computed light in galaxies in the field is about 10%. On the other hand, comparing the IC surface brightness with the smoothed out surface brightness of galaxies from Bingelli et al. (1987) gives an upper limit of about 40%.
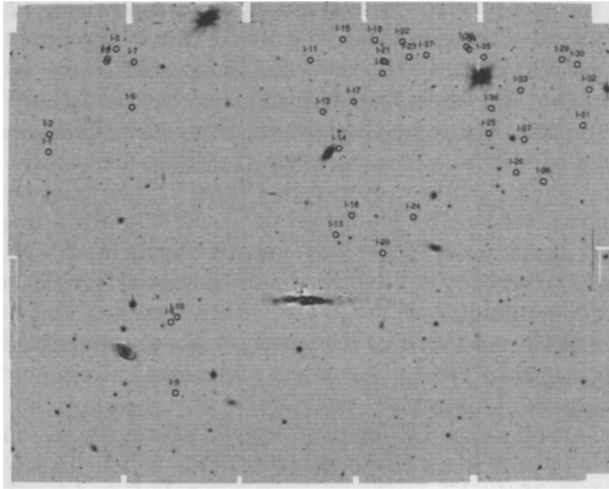

Figure 3.   Deep [OIII] image of the Virgo central core region. The ICPN candidates are marked by circles. Envelopes of bright galaxies have been subtracted. The over-density in the upper right quadrant of this field is highly significant. The majority of candidates seem to be related to the M86-M84 region of the Virgo cluster, supporting a local origin for the ICPNe.

Is the diffuse light in the Virgo cluster distributed uniformly? Recent discoveries of low surface brightness arcs in other nearby clusters, as discussed in Section 2, significant field-to-field variations in the number density of Virgo ICPNe, and the remarkably inhomogeneous distribution of ICPNe in the field surveyed by Okamura et al. (2002), see Figure 3, have demonstrated that intracluster stars are not distributed uniformly.

An emission line survey carried out on an empty field in the Leo group, using the same selection criteria as adopted for the Virgo cluster survey, gives an upper limit on the diffuse surface luminosity of 4.4×10^{-3} $L_{B,\odot}$ pc^{-2}, corresponding to a surface brightness limit $\mu_{B,*} > 32.8$ mag arcsec^{-2} (Castro-Rodriguez et al. 2003). This empty field survey, observed at the peak of the HI distribution in

the Leo intra-group cloud, gives an upper limit on the fraction of diffuse light in this intra group field of $< 1.6\%$. The evidence coming from the Leo group is very interesting because it shows that the fraction of diffuse light vs. light in individual galaxies that we find in Virgo is related to the Virgo cluster and its evolution. It does not appear to be a general physical property of the local universe. All independent measurements carried out in the Virgo cluster IC fields place the lower limit to the fraction of diffuse light to 10% of the light in individual galaxies.

6.   Intracluster stellar population properties from N-body cosmological simulations

Napolitano et al. (2003) used a high resolution simulation of a Virgo-like cluster in a ΛCDM cosmology to predict the velocity and the clustering properties of the diffuse stellar component in the intracluster region at the present epoch. 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. At the end of the simulation, the total cluster mass is $\sim 3 \times 10^{14} M_\odot$. 0.5 million particles are within the cluster virial radius; each particle has a mass of $0.5 \times 10^9 M_\odot$ and the spatial resolution is 2.5 kpc.

Napolitano and collaborators adopt an empirical scheme to identify tracers of the stellar component in the simulation and hence study its properties. Stellar tracers are those particles in the simulation within local over-densities higher than $\sim 10^4 \times \rho_{crit}$ at any given time before $z > 0.25$, which is considered the epoch when star formation stopped in the cluster. The size of an over-density region with $12000 \times \rho_{crit}$ has a linear dimension of 15 kpc at $z = 0$, and 12 kpc at $z = 3$: this simple criterion selects particles in the central regions of dark halos whose size is comparable to galaxy luminous parts. The conversion from stellar-mass-particle to ICPNe is based on the assumption that at $z = 0$ the luminous M/L ratio of the harassed stellar matter is that of an evolved stellar population, like that of M31, and the number of ICPNe for a given stellar-mass are derived from an $M/L \simeq 6$ and the luminosity-specific PN density $\alpha_{1,B} = 9.4 \times 10^{-9} \mathrm{PN\,L}_{\odot,B}^{-1}$ (Ciardullo et al. 1989).

Napolitano et al. (2003) find that at $z = 0$ the ICL 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: the two-dimensional phase space diagrams, see Figure 4, show filaments, cluster of particles and large empty regions, while dark matter particles are not clustered in the same fields. The simulations predict the radial velocity distribution expected in spectroscopic follow-up surveys. When they compare the spatial clustering in the simulation with the properties of the Virgo IC stellar population, a substantial agreement is found.

7.   Conclusions

Surface brightness photometry and direct detection of individual stars give an estimate for the fraction of diffuse light in rich clusters: it amounts to $\sim 20\%$
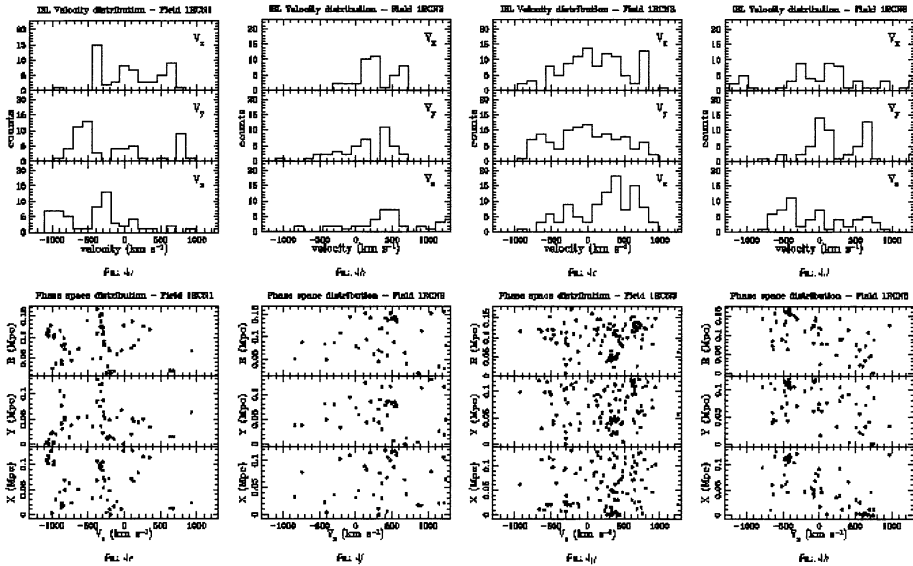
Figure 4.   Velocity distribution and projected phase-space diagram for the intracluster stellar population, from Napolitano et al. (2003).

of the light in individual cluster galaxies. In the nearby universe, the results obtained so far from ICPNe samples in the Virgo cluster have shown that the fraction of the diffuse light in the cluster amounts to 10%-40%, the intracluster stars are not centrally condensed and not uniformly distributed and the front edge of the Virgo cluster is about 20% closer to us than M87.

A high-resolution collisionless N-body simulation of a Virgo-like cluster at $z = 0$ (Napolitano et al. 2003) predicts strong substructure in phase-space, so the next goal will be to look for substructure in the radial velocity distribution of ICPN candidates in Virgo. The VLT instruments, FLAMES and VIMOS, will be most important in giving us the radial velocity distribution of the stars in the diffuse component, identifying individual streams, and providing us with samples of the phase space for the diffuse component at different cluster radii. These observational results will be compared with N-body high resolution cosmological simulations and in this way we should be able to determine how old dynamically the diffuse light is.

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