Intracluster Planetary Nebulae in the Virgo Cluster: Tracers of Diffuse Light

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Discovery of diffuse light in clusters

Stars are usually observed to form in galaxies (discs, 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, tidal stripping and cluster accretion. 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 (DM) 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.

Recently 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.

Direct observations of stars in Virgo field

Ferguson, Tanvir & von Hippel (1998) first looked for individual RGB stars in intracluster space. Using a HST deep F814W (*I*-band) image of a "blank" field located 45' east of the central Virgo Cluster galaxy M87, they were able to detect an excess of point sources relative to the HDF-north caused by the presence of IC red giants. Follow-up studies on a different IC field 41′ northwest of M87 confirmed an excess of objects (with respect to background HDF-N and HDF-S fields) with $I \geq 27$.

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. The spectrum of this isolated compact HII region is shown in Figure 1. This HII region is powered by a small star cluster of ~ 400 $M_\odot$, involving only 1 or 2 O stars, with an estimated metallicity of Z = 0.4. The age of this HII region is ~ 3 Myr and it will probably dissolve by internal processes in a few 10^8 yr: its stars and metals will then be added to the diffuse stellar population nearby. The location of this object in the Virgo field is shown in the ESO press release 02/03.

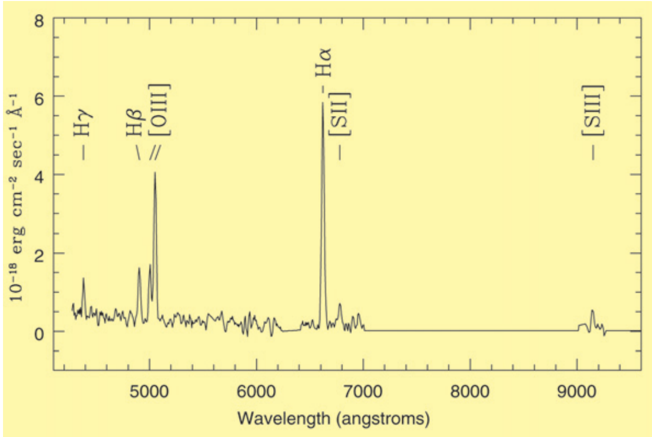

Figure 1: The emission spectrum of the compact Virgo cluster HII region obtained with UT4 and FORS2.

Intracluster Planetary Nebulae as tracers of cluster evolution

Intracluster planetary nebulae (IC PNe) have several unique features that make them ideal for probing intracluster starlight. 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.

IC PNe 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, 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 and tidal stirring, then a fraction of IC light may still be located in long streams, and dynamically unmixed structures should be easily visible in phase space.

Narrow-band wide-field surveys

We have embarked on a narrow-band [OIII] imaging survey in the Virgo cluster (Figure 2), 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, we also obtain valuable information on the 3D shape of the Virgo cluster from these IC PN samples (see also Feldmeier et al. 1998).

Wide-field mosaic cameras, such as the WFI on the ESO MPI 2.2 m telescope and the Suprime Cam on the

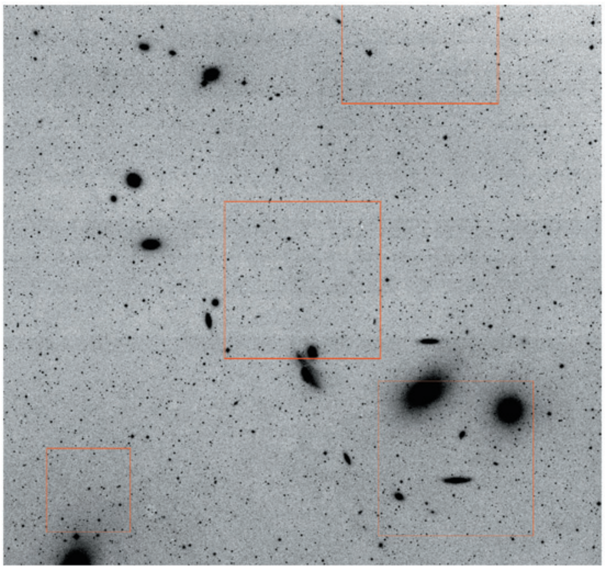

Figure 2: Our surveyed fields in the Virgo cluster. The two upper fields were obtained at the ESO MPI 2.2m telescope, and the lower-right field with the Suprime Cam at the 8.2 m Subaru telescope. The lower-left field is from Feldmeier et al. (1998) and was used to test the selection criteria on the spectroscopically confirmed IC PNe 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.

Subaru 8.2 m, allow us to identify the IC PNe 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 colour-magnitude diagrams (CMD) produced with *SExtractor*.

Through this work, the on-band/off-band [OIII] imaging technique which has been used for PNe identification in Virgo and Fornax ellipticals has led to the following selection criteria for the most reliable detection of IC PNe candidates:

1. the source should be unresolved;
2. the source should have an emission line equivalent width (EW) larger than 100 Å. This is evaluated by measuring the ([OIII] - *V*) colour 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 colour 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 colour selection must take into account the photometric errors in the final on-image, via simulation of unresolved sources.

Spectroscopic confirmation and first results

The spectroscopic observations of the Feldmeier et al. (1998) Virgo IC PNe sample, carried out by our group using 2dF and the AAT, showed that most of the emission line sources in this sample are indeed IC PNe, 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 IC PN in the Virgo cluster (Figure 3) was obtained for the first time at the VLT-UT4 with FORS2 by Arnaboldi et al. (2003). We conclude that the existence of IC PNe 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 Ly-α emitters at $z = 3.1$; see Figure 4.

We can compare the LF for the Ly-α emitters with the LF for the 16 spectroscopically confirmed IC PNe of the Feldmeier et al. (1998) sample. These confirmed IC PNe are mostly brighter than the brightest of the Ly-α emitters shown in Figure 4. The brightest of the emission line candidates studied by Kudritzki et al. (2000) is 0.5 mag fainter than the bright cut-off in the PNLF for M87, and 0.8 mag fainter than the bright cut-off for the spectroscopically confirmed IC PNe in the Virgo cluster. Most of the current IC PN candidates in Virgo are within 1 mag of the bright cut-off in the PNLF. This is the reason why Kudritzki et al. did not find IC PNe. Their sample was dominated by the Ly-α emitters which are more abundant at fainter magnitudes. (See also Arnaboldi et al. 2002).

The bright cut-off of the LF for the Virgo IC PNe 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 Ly-α emitters in the first magnitude of the LF for the Virgo IC PNe samples ? When we compute the fraction of Ly-α emitters which can contaminate the ICPN candidate sample selected as outlined in section 2.1, it amounts to about 15% of the observed sample. This estimate is supported by the empty field survey of Castro-Rodriguez et al. (2003).

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 centre, the IC PNe 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 $\mu_{B,\star} = 28–27.7$ 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 IC PNe is nearly constant. Therefore, from the data available so far, the IC PNe 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 IC PNe are produced by phenomena acting locally, as the structure in the IC PNe 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%.

Is the diffuse light in the Virgo cluster

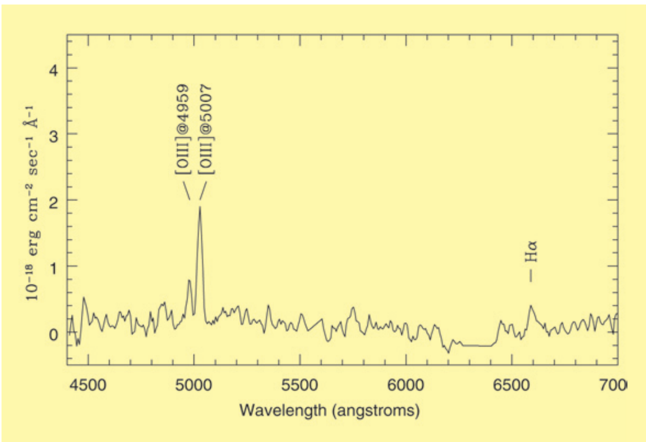

Figure 3: Spectrum of the confirmed intracluster PN in the Virgo cluster. The [OIII] doublet and the Hα emission are visible in this high S/N spectrum from UT4 and FORS2.

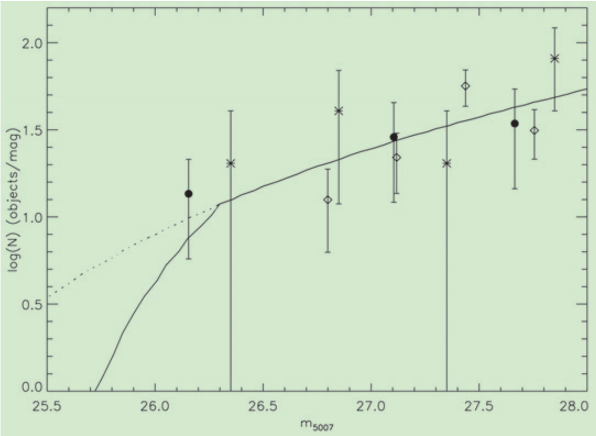

Figure 4: The solid line shows the expected LF of the field Ly-α population at redshift z = 3.1 for objects with V < 24.73. The faint dotted line shows the expected Ly-α LF without any magnitude constraints in the V band. Asterisks indicate the LF of spectroscopically confirmed Ly-a emitters from Kudritzki et al. (2000). Filled dots and diamonds show the LF of Ly-α emitters in two other blank-field surveys. These are all consistent; from Castro-Rodriguez et al. (2003).

distributed uniformly? Recent discoveries of low surface brightness arcs in other nearby clusters, significant field-to-field variations in the number density of Virgo IC PNe, and the remarkably inhomogeneous distribution of IC PNe in the field surveyed by Okamura et al. (2002) (see Figure 5) 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 $\times 10^{-3}$ $L_{B,\odot}/pc^2$, 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 intragroup 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.

A high resolution simulation of a Virgo-like cluster in a LCDM 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. We 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 centre. The simulations predict the radial velocity distribution expected in spectroscopic follow-up surveys. When we compare the spatial clustering in the simulation with the properties of the Virgo IC stellar population, we find a substantial agreement.

Conclusions

The results obtained so far from IC PNe samples have shown that *i)* the fraction of the diffuse light in the Virgo cluster amounts to 10%-40%; *ii)* the intracluster stars of Virgo are not centrally condensed and not uniformly distributed and iii) 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 $z = 0$ predicts strong substructure in phase space, so our 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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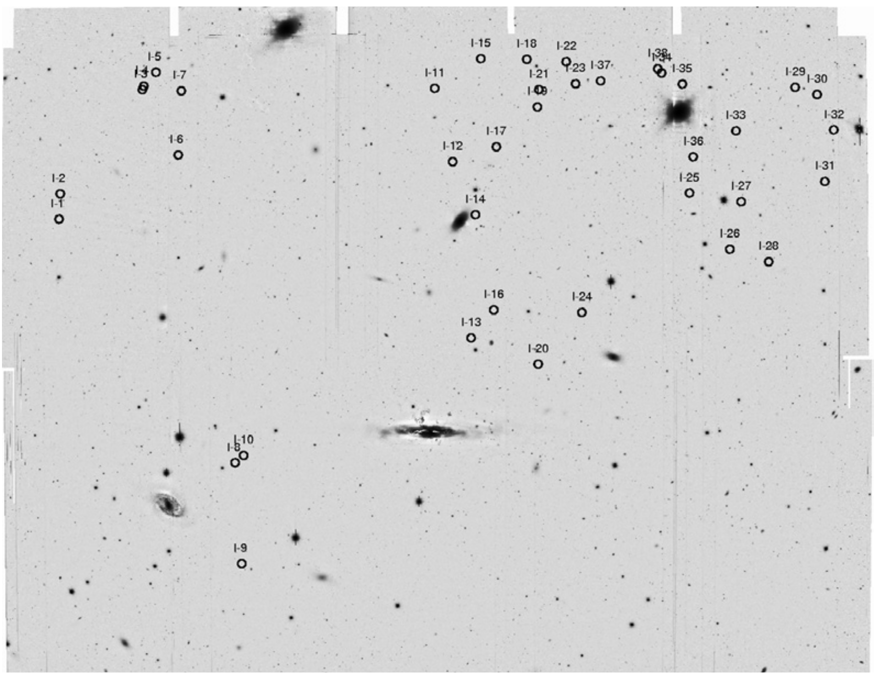

Figure 5: Deep [OIII] image in the Virgo central core region. The IC PN candidates are marked by circles. Envelopes of bright galaxies have been subtracted. The overdensity in the upper right quadrant of this field is highly significant. The majority of candidates in this field seem to be related to the M86-M84 region of the Virgo cluster, supporting a local origin for the IC PNe.