Intracluster Planetary Nebulae as Probes of Intracluster Starlight

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Abstract. I review the progress in research on Intracluster Planetary Nebulae (IPN). Hundreds of IPN candidates have now been found in the Virgo and Fornax galaxy clusters, and searches of two nearby galaxy groups have made. From the results thus far, approximately 10–20% of all stars in Virgo and Fornax are in an intracluster component, but there are few such stars in galaxy groups. From the spatial distribution of IPN, it appears that the intracluster stars are clustered, in agreement with tidal-stripping scenarios. In Virgo, the IPN have a large line-of-sight depth, which implies that the bulk of intracluster stars in this cluster derive from late-type galaxies and dwarfs. I also discuss other important developments in IPN research such as the detection of intracluster H II regions, a possible detection of IPN in the Coma Cluster, and future observational and theoretical developments.

1 Introduction

Why do planetary nebulae (PN), which are a late phase of stellar evolution, make excellent tracers of intracluster stars, stars between the galaxies inside of a galaxy cluster? An example of the utility of PN under similar circumstances can be seen in Figure 1. On the left is a standard broad-band image of the famous interacting galaxy pair M 51. Although there are numerous signs of the interaction at high surface brightnesses, there are many lower surface-brightness features [5] that are barely visible in this representation.

However, the distribution of PN found in M51 [20] displayed on the right give additional information on this interacting system. There is a clear tidal tail structure to the west of the secondary galaxy, and there are also signs of an extension of the spiral arm to the south. The lack of PN in the central regions of the galaxies are due to crowding effects. What this illustration reminds us is that *planetary nebulae trace stellar luminosity, not stellar surface brightness.* Because PN are an end-phase of stellar evolution for most stars between 1–8 solar masses, the distribution of planetary nebulae closely follows the distribution of stars in galaxies [9]. If there is enough luminosity in a stellar population for sufficient numbers of PN to be present, then we can detect and study that population, regardless of its surface brightness. Intracluster stars, which are believed to be quite luminous (anywhere between 10% and 70% of the cluster's total stellar luminosity; [51,41]), but have a very low surface brightness (less than 1% of the night sky in the optical bands; [30,22]) are therefore an ideal target for PN searches.

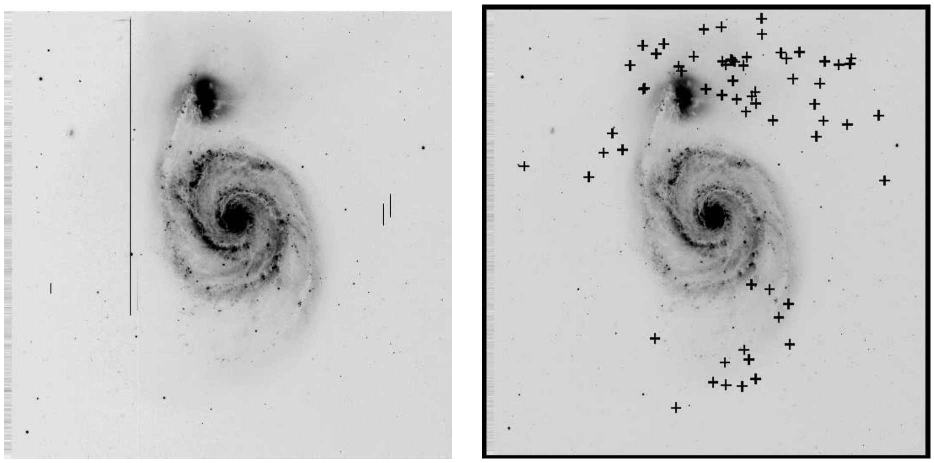

Fig. 1. Two images of the interacting galaxy pair M51. On the left is a broad-band image taken with the KPNO 4-m telescope showing the classical high-surface brightness features of this interacting system. On the right shows the location of the 64 planetary nebula candidates found by [20]. Note the clear tidal tail structures that are extremely difficult to detect in the broad-band image, but can be seen easily in the PN distribution.

PN have additional features that make them useful probes of intracluster starlight. Because PN are emission-line objects, any bright PN that can be detected photometrically can also be observed spectroscopically to high precision ($\sigma \approx 12$ km s^{-1}). In the case of M 51, spectroscopic follow-up of the PN [18] found that the western tidal tail consists of two discrete structures that overlap in projection, one from each galaxy. With the high velocity precision of the PN observations, the separation of the two kinematic structures was trivial. Although I will not focus on the dynamical aspects of IPN/PN in this review (see reviews by Arnaboldi, Douglas, Gerhard, & Peng this conference), it is important to state that IPN are the easiest (and perhaps, the only) way to obtain dynamical information about the intracluster light.

Finally, through the [O III] λ 5007 Planetary Nebulae Luminosity Function (PNLF), extragalactic PN make excellent distance indicators (see Ciardullo, this conference). The distinctive PNLF can be used in the intracluster environment to gain information on the line-of-sight distribution of the intracluster stars.

Why study intracluster stars in the first place? Once a curiosity proposed by Zwicky ([62]), intracluster light is potentially of great interest to studies of galaxy and galaxy cluster evolution. The dynamical evolution of cluster galaxies is complex, and involves the poorly understood processes of cluster accretion and tidal stripping [14]. The intracluster light provides a unique way to study these mechanisms. Modern numerical simulations show that the intracluster light [15,44,55,59,39] has a complex structure, and can be used to gain information on the dynamical evolution of galaxies and galaxy clusters.

2 History of Intracluster Planetary Nebulae Research

The history of IPN research begins over a decade ago with the first PN survey of the Virgo cluster [32] (hereafter JCF). In this survey of elliptical galaxies, JCF found 11 PN that were much brighter than the expected [O III] λ 5007 PNLF cut-off magnitude. JCF attempted to explain these "overluminous" PN with a number of hypotheses, but none was entirely satisfactory.

The next step involved spectroscopic follow-up of objects from the JCF survey. During a radial velocity survey of PN in the Virgo elliptical galaxy M 86, [1] found that 16 of the 19 detected PN velocities were consistent with the galaxy's mean velocity (v_{radial} = -227 km s^{-1}). The other three planetaries had mean radial velocities of $\sim$ 1600 km s^{-1}, more consistent with the Virgo cluster's mean velocity. [1] argued convincingly that these objects were intracluster planetary nebulae, and it is here that the term first enters the literature. The "overluminous" PN candidates were thus naturally explained as a population of intracluster stars in front of the target galaxies. Almost simultaneously, the first search for IPN candidates in the Fornax cluster was published [57], and more detections of IPN candidates in Virgo quickly followed [36,10,21].

However, a surprise was in the works. Spectroscopic follow-up of the IPN candidates revealed that some were not IPN, but instead background emission-line objects with extremely high equivalent width [27,34]. This was unexpected, because previous deep emission-line surveys had found very few such objects [48], though many have now been detected at fainter magnitudes [50]. The most likely source of the contamination was found to be Lyman-α galaxies at redshifts 3.12–3.14, where the Lyman-α λ 1215 line has been redshifted into the [O III] λ 5007 filters used in IPN searches. However other types of contaminating objects may also exist [56,46].

Although these contaminants caused some consternation at first, a number of lines of evidence quickly showed that the majority of IPN candidates are in fact, actual IPN. Observations of blank control fields with identical search procedures as the IPN surveys [11,7] have found that the contamination fraction is significant, but was less than the observed IPN surface density. The surface densities found correspond to a contamination rate of $\approx$ 20% in the Virgo cluster and $\approx$ 50% in Fornax (Fornax is more distant than Virgo, so its PNLF is fainter, and therefore further down the contaminating sources luminosity function). There are still significant uncertainties in the background density due to large-scale structure, and to the small numbers of contaminating objects found thus far. However, deeper and broader control fields are forthcoming. Spectroscopic follow-up of IPN candidates [27,11,3], and Arnaboldi et al., this conference, clearly show large numbers of IPN candidates have the expected [O III] λ 5007 and 4959 emission lines, with a contamination rate similar to the blank field surveys. Finally, there is independent evidence of individual intracluster stars in Virgo from observations of individual Intracluster Red Giant stars (IRGs; [26,17]) from the *Hubble Space Telescope*.

It is worth reiterating that *all* deep [O III] λ 5007 emission-line searches will have such contamination at fainter magnitudes. In fact, such objects have already been seen in conventional PN surveys ([37,18] and Romanowsky, private communication). Extragalactic PN researchers should keep this into account. The brightest of such objects have been detected with a m_{5007} magnitude of 25.5 [27], though the luminosity function of the contaminants is still poorly known.

Currently, with the widespread use of mosaic CCD detectors, and automated detection methods derived from DAOPHOT and SExtractor, over a hundred IPN candidates can be found in a single telescope run [47,23,3,25]. IPN candidates are easily identified as stellar sources that appear in a deep [O III] λ 5007 image, but completely disappear in an image through a filter that does not contain the [O III] line. Currently, over 400 IPN candidates have been detected in the Virgo cluster, and over 100 IPN candidates have been found in the Fornax cluster. Figure 2 summarizes the status of the different surveys. Despite all of the effort, to date, only a few percent of the total angular area of Virgo and Fornax have been surveyed. Literally thousands of IPN wait to be discovered by 4-meter class telescopes.

3 The Spatial Distribution of the Intracluster Light

If we want to understand the mechanisms that produce intracluster stars, it is useful to compare the intracluster stars' spatial distribution with that of the better-studied components of galaxy clusters: the cluster galaxies, the hot intracluster gas, and the invisible dark matter. Theoretical work predicts very different spatial distributions for the intracluster light depending on its production time. For example, if most intracluster stars are removed early in a cluster's lifetime [38], the distribution of this diffuse component will be smooth and follow the cluster potential. However, if a significant portion of the stars are removed at late epochs via galaxy encounters and tidal stripping [51,42], then the intracluster light should be clumpy and have a non-relaxed appearance. In particular, the "harassment" models of [42,43] first predicted that many intracluster stars will exist in long ($\sim$ 2 Mpc) tidal tails, which may maintain their structure for Gyrs.

With regards to angular clustering, there is good evidence that the IPN follow a non-random distribution. [47,25] show evidence for clumps of IPN within their survey fields, and Aguerri et al. (2004) found a strong clustering signal using a standard two-point correlation function analysis (reported in [45]). The scale of the angular clustering ranges from one to ten arcminutes, (corresponding 5 to 50 kpc assuming a mean Virgo distance of 15 Mpc), depending on the field studied. However, no tail-like features have yet been seen in the IPN distribution, although tidal arc features have been seen in broad-band images of other galaxy clusters [58,31,6].

With the use of the [O III] λ 5007 PNLF, we can also obtain line-of-sight information on the intracluster stars, a property unique to IPN. Although a full analysis of the observed luminosity functions has not yet been attempted, we can already learn something useful from the brightest IPN candidates in each

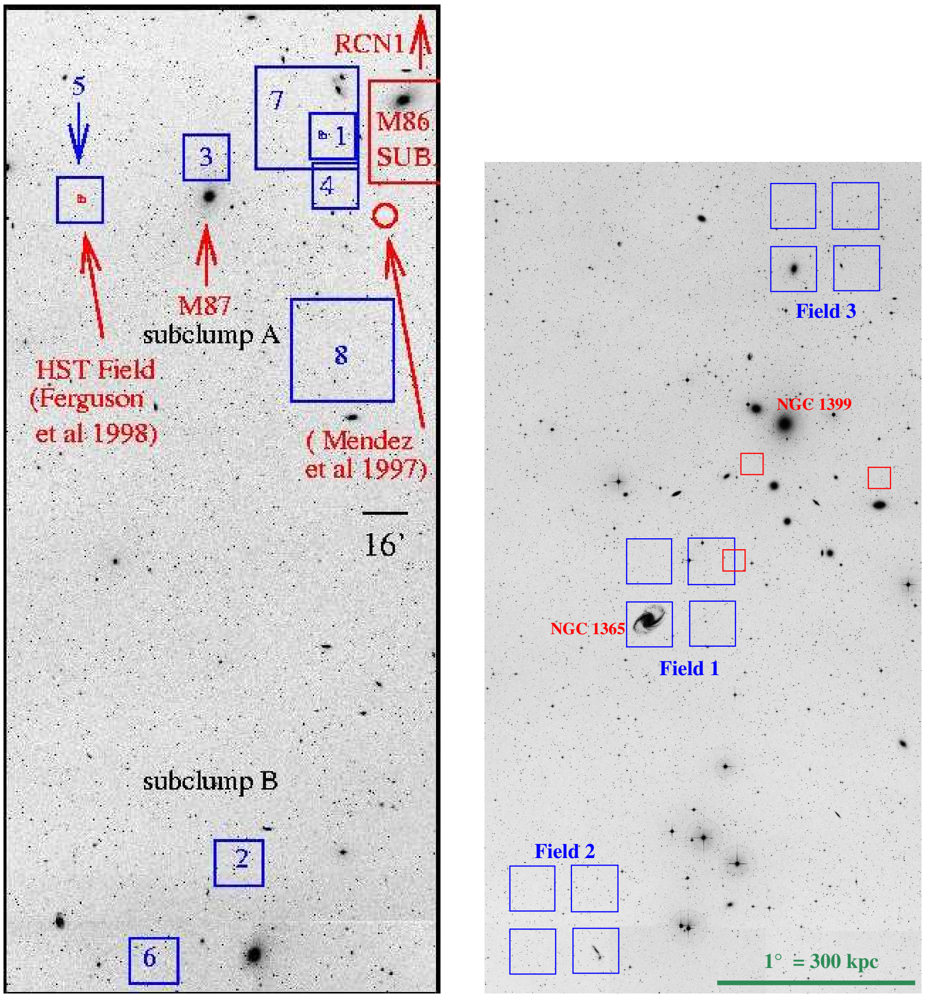

Fig. 2. Images of the Virgo cluster (left), and the Fornax cluster (right), with the various published IPN survey fields marked, as well as the two *HST* IRG fields. Soon to come are additional fields from Aguerri et al. (2004; Virgo), Ciardullo et al. (2004; Fornax), Feldmeier et al. (2005; Virgo) and Ciardullo et al. (2005; IRG Virgo)

field. Given the empirical PNLF, there is a maximum absolute magnitude M^*, that a PN may have in the light of [O III]. If we assume that the brightest observed IPN candidate in each field has this absolute magnitude, we can derive an upper limit on its distance, and therefore estimate the distance to the front edge of the Virgo intracluster population. This is plotted in Figure 3. As can be clearly seen, there is an offset between the IPN of subclusters A and B : this is interpreted as due to the differing distances of these two subclusters. However, the most revealing feature of the distribution of the IPN is in subclump A. The upper limit distance for most of the fields is well in front of the cluster core. This is partially due to a selection effect: it is easier to detect an IPN on the near side of Virgo than the far side. Nevertheless, the depth implied from the measurements is remarkable. If we take the data at face value, then the IPN distribution has a line-of-sight radius of over 4 Mpc. If we compare this radius to the classical radius of Virgo on the sky (six degrees, or 1.6 Mpc), we find that the Virgo cluster is more than 2.6 times as deep as it is wide. Virgo is nowhere near a spherical cluster: it contains considerable substructure, and is elongated significantly along our line of sight.

The great depth derived for the IPN distribution gives an important clue to the parent galaxies of the intracluster stars. Numerical simulations [43,16] show that the majority of intracluster stars are ejected into orbits similar to that of their parent galaxies. In Virgo, the cluster ellipticals are clustered within a radius of ≈ 2 Mpc from the cluster core [32]. In contrast, the hydrogen deficient spirals found in the Virgo cluster have a radius of 4 Mpc or larger [54], and the dwarf ellipticals have a depth of 6 Mpc [33]. Therefore, it seems clear that a significant portion of Virgo's intracluster stars originate from late-type galaxies whose highly radial orbits take them in and out of the cluster core.

4 Converting IPN densities to Luminosity Densities

In principle, determining the amount of intracluster luminosity from the observed numbers of IPN is straightforward. Theories of simple stellar populations [49] have shown that the bolometric luminosity-specific stellar evolutionary flux of non-star-forming stellar populations should be $\sim 2 \times 10^{-11}$ stars-yr^{-1}-$L_{\odot}^{-1}$, (nearly) independent of population age or initial mass function. If the lifetime of the planetary nebula stage is $\sim 25,000$ yr, and if the empirical PNLF is valid to ~ 8 mag below the PNLF cutoff, then every stellar system should have $\alpha \sim 50 \times 10^{-8}$ PN-$L_{\odot}^{-1}$. According to the empirical PNLF, approximately one out of ten of these PNe will be within 2.5 mag of M^*. Thus, under the above assumptions, most stellar populations should have $\alpha_{2.5} \sim 50 \times 10^{-9}$ PN-$L_{\odot}^{-1}$. The observed number of IPN, coupled with the PNLF, can therefore be used to deduce the total luminosity of the underlying stellar population.

In practice, there are a number of systematic effects that must be accounted for before we can transform the numbers of IPN to a stellar luminosity [25], which we briefly summarize here.

First, although stellar evolution theory originally predicted a constant $\alpha_{2.5}$ value for all non star-forming populations, observations present a more complicated picture. [8] found that in a sample of 23 elliptical galaxies, lenticular galaxies, and spiral bulges, the observed value of $\alpha_{2.5}$ never exceeded $\alpha_{2.5} = 50 \times 10^{-9}$ PN-$L_{\odot}^{-1}$ but was often significantly less, with higher luminosity galaxies having systematically smaller values of $\alpha_{2.5}$. Since the amount of intracluster starlight derived is inversely proportional to the $\alpha_{2.5}$ parameter, a large error in the amount of intracluster light can result if this is not accounted for.

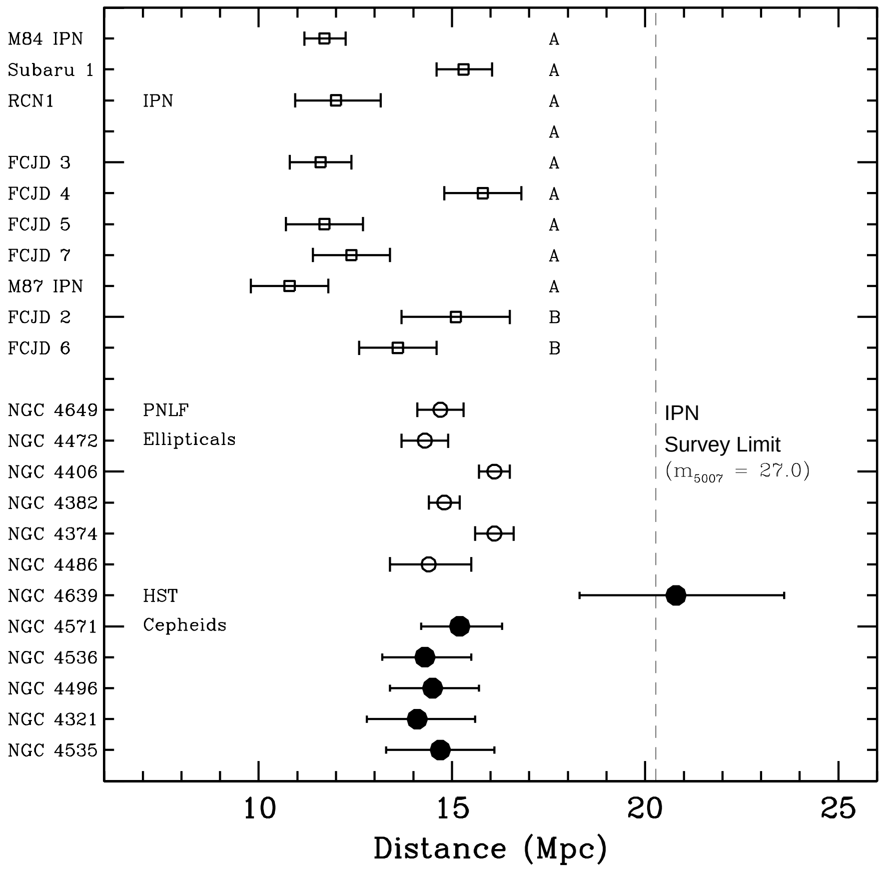

Fig. 3. A comparison of the upper limit distances obtained from the intracluster planetary nebulae to direct distances to Virgo Cluster galaxies. At the top are the upper limit distances (denoted by the open squares) from IPN observations by Okamura et al. (2002) and Arnaboldi et al. (2002). Below that are the distances derived from as the overluminous IPN found in front of M87 (Ciardullo et al. 1998). These upper limit distances are compared to the PNLF distances of Virgo ellipticals (denoted by the open circles; Jacoby, Ciardullo, & Ford 1990; Ciardullo et al. 1998), and Cepheid distances to spiral galaxies (denoted by the filled circles; Pierce et al. 1994; Saha et al. 1997; Freedman et al. 2001). The subcluster of Virgo that each intracluster field resides in is noted. Note the great depth of IPN, compared to that of the elliptical galaxies.

By comparing the numbers of IPN in a field surrounding a *HST* WFPC2 field, with RGB and AGB star counts, [17] found a value of $\alpha_{2.5} = 23^{+10}_{-12} \times 10^{-9}$ PN-$L_{\odot}^{-1}$ for Virgo's intracluster population. This observational measurement is bolstered by the new theoretical work of Buzzoni & Arnaboldi (this conference), which show that the observational value for $\alpha_{2.5}$ is well within the range for models of moderate luminosity galaxies.

Second, as we have discussed previously, IPN surveys are not pristine: approximately 20% of Virgo IPN candidates, and 50% of Fornax IPN candidates, are likely to be unrelated background sources. Although these objects are subtracted out statistically from all modern IPN surveys, the importance of field-to-field variations in the background due to large-scale structure is still unknown.

Finally, the IPN candidates of Virgo have a significant line-of-sight depth. Since the conversion between number of PN and luminosity depends on the shape of the luminosity function, this depth can change the amount of intracluster light found from the data. Models [21] indicate that the difference between a single-distance model (the most conservative) and assuming that the IPN are uniformly distributed in a sphere of radius 3 Mpc (the least conservative), changes the derived intracluster star luminosity by up to a factor of three. Thus far, all IPN researchers have adopted a single distance model in order to be conservative, but this effect is the least studied at this point.

After applying all of these corrections, the intracluster stellar fractions for Virgo vary between 10 and 20% [2,47,3,25], with the errors being dominated by the systematic effects. The IRG measurements [26,17] find somewhat less intracluster light (10–15%), but the various results agree within the errors. However, it is important to note that each of these studies makes different assumptions concerning the calculation of intracluster luminosity, the amount of light bound to galaxies, and the contamination of background sources. For Fornax, there are only two measurements of the intracluster star fraction thus far from IPN. [57] report a fraction of up to 40%, but this is before the detection of contaminating sources, and is likely to be an overestimate. Ciardullo (2004, in prep), reports an approximate fraction of 20%, with similar errors as the Virgo results. Regardless of the uncertainties, it is clear that a significant fraction of all stars in Virgo and Fornax are in an intracluster component.

How does the IPN luminosity density compare with well-known cluster properties such as radius, or projected galaxy density? [25] has compared these properties in Virgo, and has found little or no correlation. This may be due to Virgo's status as a dynamically young cluster, or due to a selection effect (IPN researchers must observe where the galaxies are not, to avoid confusion with normal extragalactic PN). More data will be needed to confirm this result.

5 Intracluster H II Regions

A recent discovery stemming from IPN searches is the detection of H II regions in the far halos of galaxies or in intracluster space. In the course of spectroscopic follow-up of a Virgo IPN field, [29] found an emission-line source that has the properties of a $\sim$ 400 solar mass, 3 Myr compact H II region, over 17 kpc away from the nearest Virgo galaxy (see also [35] for a similar, earlier, under-appreciated example). There are now a number of other examples of intergalactic star formation in Virgo and in other galaxy clusters and groups [60,53,52,13,19].

These discoveries have two important implications. First, star formation can occur at large distances from galaxies, and environments quite different than that normally studied. This has implications for a number of fields of astrophysics, including the origin of metallicity in the intergalactic and intracluster medium, and the possible in situ origin of B stars in the Galactic halo. At this time, it does appear that intracluster star formation is only a small fraction of the total intracluster star production, but the exact amount is uncertain. Second, these objects are another form of contamination to pure IPN surveys. Discouragingly, the only way to separate these objects from IPN is through deep spectroscopy. Luminous PN have [O III] / Hα ratios of two or greater [12], where luminous H II regions do not. From the surveys thus far, these objects appear to be relatively rare component of IPN surveys ($\sim 3\%$), but more study is needed in this area.

6 Intra-group Starlight

Although the presence of intracluster starlight in clusters such as Virgo and Fornax is now well established, the amount of 'intra-group' starlight is still uncertain. Theoretical studies predict that if most intracluster stars are removed by galaxy collisions [51,42], the fraction of intra-group stars, to first order, should be a smooth function of galaxy number density ($L_{ICL} \sim N^2_{Gal}$). To test this hypothesis, two different groups have surveyed the nearby M 81 and Leo groups of galaxies [7,19], using similar detection methods as the cluster searches. In both cases, no genuine intra-group PN were found. These non-detections strongly implies there is substantially less (4–15 times) less intergalactic stars in groups than there are in clusters.

When compared with other measurements of intracluster star fractions through modern deep imaging [4,30,22,24], or through the detection of intracluster supernovae [28], an interesting pattern emerges, plotted in Figure 4. For galaxy clusters, the data is consistent with an approximate fraction of 20%, albeit with large error bars or intrinsic scatter. When we move to the group environment, the fraction abruptly drops, with no sign of any smooth decline. This implies that there is something special about the cluster environment that promotes intracluster star production. More data will be needed to confirm and strengthen this result, especially IPN searches of additional galaxy groups.

7 IPN in the Coma Cluster?

At this conference, Gerhard et al. announced the possible detection of at least one IPN candidate in the Coma Cluster. If this candidate is confirmed, it will be the most distant individual PN ever detected, at a distance of over 100 Mpc. This object was found using a technique of filling the entire focal plane of the 8-m Subaru telescope with a slit mask through the appropriate [O III] λ 5007 filter, and looking for narrow-line emission sources. Deep broad-band imaging has implied that the Coma Cluster may have a very high intracluster star fraction, up to 50% [4], so it is plausible that a few IPN could be detected, despite the small

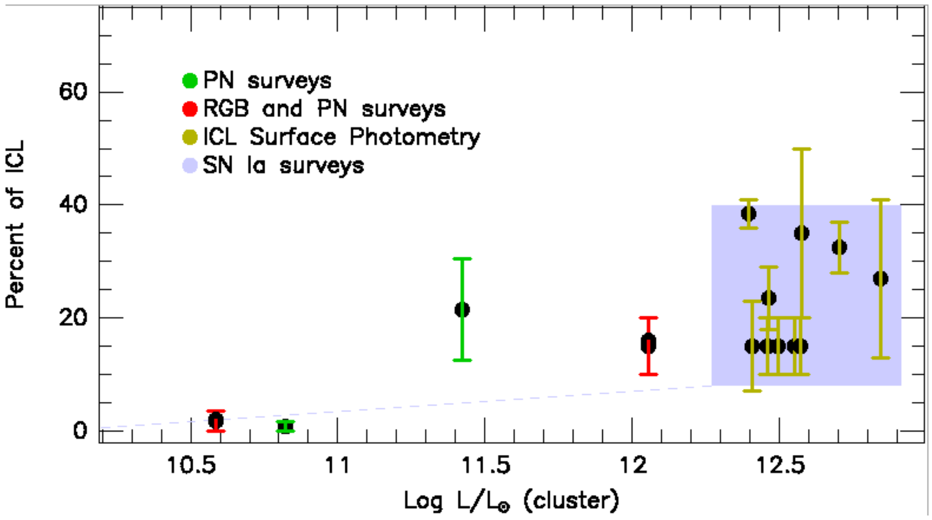

Fig. 4. A comparison of detected intracluster star fractions from modern measurements, as a function of the velocity dispersion. Note the abrupt change from the cluster environment to the group environment.

area surveyed. The most exciting aspect of this observation is that it opens up a way to observe PN at much greater distances than previously thought possible, and makes it possible to place IPN density limits in more distant galaxy clusters.

8 The Future

Studies of IPN are not even a decade old, and much more work still needs to be done. The most crucial observations needed in the near term are spectroscopic follow-up of a large number of IPN candidates. This would allow us to better determine the contamination rate from background galaxies, avoid any other intracluster H II regions, and most importantly, gain information on the kinematics of intracluster stars. More IPN imaging is needed in Virgo and Fornax at differing radii and densities, in order to confirm the lack of correlations found thus far. IPN surveys of additional galaxy groups are needed to determine the lack of intra-group stars in these systems, and to better characterize the steepness of the intracluster production "cliff."

However, the future of IPN research will involve close comparisons of IPN properties to other observations of extragalactic PN and galaxy clusters and close comparison to the modern numerical simulations now being undertaken. Some examples are given below, but it is almost certain that many more will be added in the next few years.

Villaver (this conference), presented the first numerical hydrodynamical simulations of IPN within a hot intracluster gaseous medium. The results imply that IPN do survive in the intracluster medium, but the nebula may be spatially distorted.

[40] has just completed the first phase of a deep CCD imaging survey of the Virgo cluster core using the techniques of ultra-deep surface photometry. These new observations reach extremely faint surface brightnesses ($\mu_V \approx 29.6$) over large angular areas ($\approx$ 2 square degrees). Comparing these deep imaging maps with the IPN observations should be revealing, and allow us to better determine the reality of tidal features in both data sets, and to give clear targets for follow-up IPN observations.

HST+ACS broad-band observations are planned of an intracluster field in Virgo by Summer 2005, with the goal of obtaining the first color-magnitude diagram of the intracluster stars. By placing tighter constraints on the age and luminosity of the intracluster population, we should be able to better constrain the $\alpha_{2.5}$ parameter, and improve the accuracy of the total amount of intracluster starlight.

Finally, with the advent of advanced numerical simulations of galaxy clusters, we will be able to compare the IPN data to models of intracluster star production. Due to the large angular size of nearby clusters, it will be many years before the majority of the clusters will be surveyed for IPN. Numerical simulations will hopefully allow us to survey more efficiently, and to obtain better quality information on the properties of intracluster starlight.

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