Candidates for Intracluster Planetary Nebulae in the Virgo Cluster based on the Suprime-Cam Narrow-Band Imaging in O[III] and Hα

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Abstract

We have identified 38 candidates of intracluster planetary nebulae (ICPNe) in a 34’ × 27’ field in the core of the Virgo cluster based on the Suprime-Cam imaging through two narrow-band filters centered at the redshifted wavelengths of the [OIII]λ = 5007 Å and the Hαλ = 6563 Å lines. Broad-band images in V and R bands are used to check for any emissions in the adjacent continuum. We describe the method briefly and present the list of intracluster planetary nebulae candidates, together with their finding charts. The ICPN candidates show a highly inhomogeneous distribution, which may suggest an association with the M86-M84 subcluster. Fraction of diffuse intracluster light with respect to total light in galaxies is estimated to be about 10%, leading to an estimate of about 20% for the baryon fraction. Spectroscopic follow up and a wider survey are critical to reveal the nature of intracluster stellar population.

Key words: galaxies:clusters:individual (Virgo), intracluster planetary nebulae,
1. Introduction

Recent observations show that there is a substantial amount of intracluster stellar population, which is observed as diffuse intracluster light (Bernstein et al. 1995), or as individual stars, i.e., planetary nebulae (Arnaboldi et al. 1996; Theuns and Warren 1997; Feldmeier et al. 1998), and red giant stars (Ferguson et al. 1998; see also the review by Feldmeier 2002).

The presence of this intracluster stellar population is expected from dynamical processes which unbind stars from galaxies, as predicted by interactions among galaxies ('harassment') in a cluster potential (Moore et al. 1996). However, it is also possible that some stars were formed in more or less uniform intracluster matter before the matter was assembled in individual galaxies, or as the protogalaxies were falling in the cluster potential (Merritt 1984). Those stars, if present, would have the properties similar to those of the hypothetical population III. Detection and a quantitative estimate of the amount of such a hypothetical population would have a profound impact on our understanding of the formation and evolution of galaxies and clusters of galaxies.

The presence of a diffuse stellar component in clusters is relevant also for the ongoing discussion of the baryonic mass in clusters (Fukugita et al. 1998) and the efficiency of star formation (Balogh et al. 2001). To account for the diffuse component, the total baryonic mass of a galaxy cluster, \( M_b \), should be written as:

\[
M_b = M_{gal} + M_{gas} + M_{IC*},
\]

(1)

where \( M_{gal} \) represents the mass of stars and interstellar matter which reside in galaxies, \( M_{gas} \) is the mass of hot intracluster gas, and \( M_{IC*} \) is the mass of intracluster stars. So far, \( M_{IC*} \) was neglected, while recent studies argue that it may be a significant fraction of the total baryonic mass, at least 15% and perhaps much more (Feldmeier et al. 1998; Arnaboldi et al. 2002a).

In order to address the origin and constraint the amount of the intracluster stellar population, we need to establish the properties of this population of stars. Intracluster planetary nebulae (ICPNe) are excellent tracers of the intracluster stellar population (Arnaboldi et al. 1996; Freeman et al. 2000; Arnaboldi et al. 2002a). Searches for ICPNe were carried out so far using a narrow band filter centered on the [OIII] \( \lambda 5007 \) line (Theuns and Warren 1997, Ciardullo et al. 1998, Feldmeier et al. 1998, Feldmeier 2002, Arnaboldi et al. 2002a). However, the first spectroscopic follow-up carried out on a subsample of ICPNe candidates selected via this technique showed a significant amount of contamination (Kudritzki et al. 2000, Freeman et al. 2000). One class of contaminants consists of continuum objects misclassified as line-emitters because of photometric errors. The other class includes high redshift line emitters such as [OII] starbursts at \( z \sim 0.347 \) and Ly\( \alpha \) emitters at \( z \sim 3.13 \). Contamination by continuum
objects can be solved by taking an adequate off-band images, but reducing contamination from high-z line emitters is a much more difficult problem.

To overcome the latter problem, we made a search for ICPNe in the Virgo cluster using two narrow band filters centered on the redshifted [OIII] line and Hα line, the strongest and the second strongest emission line respectively from a PN, with the Suprime-Cam on the 8.2m Subaru telescope. Such a challenging program can be carried out only with an 8 meter telescope equipped with a wide-field imager because Hα emission from a PN is 3 − 5 times weaker than the strongest λ 5007 [OIII] green line.

We present in this Letter the first results of our ongoing survey and the list of secure candidates for ICPNe in the core of the Virgo cluster, together with their finding charts. New estimates are provided for the lower limit of the intracluster stellar population and the fraction of baryonic matter in the Virgo cluster core. Extensive discussion of the candidate selection criteria and the results of the spectroscopic follow up are given in Arnaboldi et al. (2002b).

2. Observation and Data Reduction

In March-April 2001, a field in the central region of the Virgo cluster was observed during the commissioning of the Suprime-Cam 10k×8k mosaic CCD camera (Miyazaki et al. 2002) at the prime focus of the 8.2m Subaru telescope. The camera covered an area of 34′ × 27′ with a resolution of 0.2″ per pixel. The field is just south of M84-M86 (α = 12h25m47.′0, δ = +12°43′58″: J2000).

The field was imaged through two narrow band filters which have (λc, ∆λ)=(5021Å, 74Å) and (6607Å, 101Å), corresponding to the redshifted [OIII] and Hα lines, respectively. Two standard broad band filters (V and R) were also used to check the intensity in the adjacent continuum. Total exposure times are 900 sec, 720 sec, 3600 sec, and 8728 sec for V, R, [OIII], and Hα, respectively. The seeing was slightly better for the narrow bands (0.′6 − 0.′7) than for the broad bands (0.′75 − 1.′0).

Data reductions, including an astrometric solution, were carried out with a data reduction package developed by the Suprime-Cam team. All the reduced images in the same band were coadded and normalized to 1 sec exposure. We then used a combined (V + R) continuum image, following the procedure adopted by Steidel et al. (2000) to check for any emission in the continuum.

We use SExtractor (Bertin and Arnouts 1996) to carry out the detection and photometry. Because the [OIII] image is the deepest, we perform the source detection on the [OIII] image and then compute aperture magnitudes for the Hα and (V + R) images at the location of the [OIII]-detected objects.

Our selection criteria are based on our instrumental magnitudes. Limiting magnitudes

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1 one 2k×4k chip was dead in the March run.
Table 1. Limiting magnitudes and detection limits in the instrumental magnitudes

| Band       | (V + R) | [OIII] | Hα |
|------------|---------|--------|----|
| m\textsubscript{lim} | -2.3    | 1.8    | 1.2|
| m\textsubscript{det}   | -2.0    | 2.1    | 1.5|

and detection limits are derived from the simulation described in Arnaboldi et al. (2002a), and shown in Table 1. The former is the magnitude at which 50% of the input sample is retrieved from the simulated image, while the latter is the magnitude at which the fraction of retrieved point sources becomes zero.

The calibration of our \( \lambda \) 5007 [OIII] fluxes to the \( m(5007) \) magnitude system by Jacoby (1989) is addressed in Arnaboldi et al. (2002b). We report here that \( m(5007) = m([\text{OIII}]) + 26.30 \pm 0.05 \) and \( V = V_{\text{inst}} + 28.0 \pm 0.05 \), where \( m([\text{OIII}] \) and \( V_{\text{inst}} \) are the instrumental magnitude for a 1 second exposure in the [OIII] and \( V \) bands respectively.

3. Selection Criteria for ICPNe Candidates

We have developed a robust technique for the identification of ICPNe based on the two-color diagram, ([OIII] - Hα) versus ([OIII] - (V+R)). We can classify the objects we detected into four broad classes according to their location on the two-color diagram; (a) secure PNe candidates which are detected in both [OIII] and Hα, (b) high excitation PNe or high EW Lyα which are detected in [OIII] and have very weak (due to residuals in the sky subtraction) or negative flux in both \( (V + R) \) and Hα (This class probably has a small amount of contamination by high-z emission line galaxies), (c) high-z galaxies with Lyα or [OIII] emission in our [OIII] band, with some flux in \( (V + R) \) and weak or negative flux in Hα, (d) continuum objects such as ordinary stars and galaxies. Full discussion and quantitative criteria are given in Arnaboldi et al. (2002b).

Our field includes two bright Virgo ellipticals, M86 (NGC4406) and M84 (NGC4374), which were surveyed for PNe by Jacoby et al. (1990) using the on-off band technique, i.e., only one narrow band filter centered on the redshifted [OIII] line. We matched the list of published PNe candidates with the sources that we detected. We classified the matched objects and obtained the results summarized in Table 2.  

We note that the identification of PNe in individual galaxies via the on-off band technique and the "by-eye" identification produce catalogues with a significant fraction, 39% and 56% in M84 and M86 respectively, of continuum objects and line emitters with detected continuum, which we know cannot be true PNe.

Table 3 summarizes the secure candidates of ICPNe identified in this study, i.e., those which are classified as (a) and are located outside of \( 4r_e \times 4r_e \) areas centered on M84, M86 and

\(^2\) M86 is partially out of our image and we could match only about 1/3 of the Jacoby et al. (1990)'s sample.
Table 2. Statistics of the sample matched with Jacoby et al. (1990)’s.

| Galaxy  | Matched total | class (a) | (b) | (c)+(d) |
|---------|---------------|----------|-----|---------|
| M84     | 74            | 19       | 26  | 29      |
| M86     | 64            | 13       | 15  | 36      |

NGC 4388, where $r_e$ is the effective radius in which a half of the total luminosity is included. Over-luminous objects in the M84 fields are also included because they may be ICPNe on the near side of the cluster, according to Ciardullo et al. (1998).3

4. Projected Distribution of the Candidates

Distribution the ICPN candidates projected on the sky is shown in Figure 1 on our deep [OIII] image. The lower left area bounded by the black line indicates the area excluded from our survey because of the dead CCD chip.

Figure 1 shows a remarkably inhomogeneous distribution of the ICPN candidates. Even when the over-luminous objects are not considered, the overdensity in the upper right quadrant of our field is highly significant. The majority of the candidates seem to be related with the M86-M84 region of the Virgo cluster, which suggests a local origin for the ICPNe. They may be bound in the halos of these galaxies, or they may have become unbound from these galaxies while they are falling into the Virgo cluster (e.g., Binggeli et al. 1993; Rangarajan et al. 1995). If the latter is the case, the highly inhomogeneous distribution is possibly a hint of a very recent harassment event. There are also several candidates which do not seem to be associated with bright galaxies.

Two of the three dominant galaxies have radial velocities largely different from the mean velocity of the Virgo cluster (1050±35 kms$^{-1}$; Binggeli et al. 1993); M84 (1060 kms$^{-1}$), M86 (−244), and NGC 4388 (2524). A spectroscopic follow up and a wider survey are badly needed to clarify the nature of the parent stellar population of ICPNe.

Figure 2 presents the finding charts of the 38 candidates.

5. Fraction of Diffuse Light and Baryon Fraction

Our goal is to estimate the fraction of diffuse light coming from the intracluster stellar population and the baryonic fraction in the Virgo cluster core, where we have our survey data.

The crucial parameter in this evaluation is the PN specific frequency parameter $\alpha_{1.0}$ which gives the number of PNe per unit stellar B luminosity within the first 1.0 mag of the bright end cut off of the [OIII] PN luminosity function, as selected according to our criteria.

\footnote{A large depth of the Virgo cluster along the line of sight was pointed out by Yasuda et al. (1997).}
There is no theoretical prediction for its value which may well depend on the age/metallicity of the stellar population from which the PNe originate. Its value has always been derived so far from empirical measurements. Arnaboldi et al. (2002b) estimated the parameter using 45 PNe in M84 as
\[ \alpha_{1,0} = 3.46 \times 10^{-9} PNL_{B,\odot}^{-1} \]
In what follows, we adopt the distance of the Virgo cluster of D=15 Mpc (Yasuda et al. 1997).

The 36 ICPN candidates in our field excluding I-24 and I-33 imply a total associated luminosity of \(1.0 \times 10^{10} L_{B,\odot}\). However, some fraction of our candidates may still turn out to be high redshift line emitters. For this relatively bright sample selected from both [OIII] and Hα images, the fraction of high-z contaminants is probably much less than the 25% found by Arnaboldi et al. (2002a) for an [OIII]-only selected sample. In order to derive a secure lower limit, we reduce the associated luminosity to \(7.5 \times 10^{9} L_{B,\odot}\) based on the very conservative estimate. The area surveyed by the Suprime-Cam is 0.196 deg\(^2\). Thus, the distance independent surface brightness of the diffuse light is \(\mu_B = 27.69\) mag arcsec\(^{-2}\).

Next, we need to compare this with the light from the Virgo galaxies. If the intracluster stellar population is closely related to the local density of galaxies, we should compare the diffuse light with the light of three galaxies, M86\((B_T=9.83\)mag\)), M84\((10.09)\), and NGC4388\((11.76)\), which dominates the galaxy light in our field \(8.0 \times 10^{10} L_{B,\odot}\) in total). This comparison gives an estimate of 9% as the fraction of diffuse light to galaxy light. On the other hand, if the population is a large-scale phenomenon, we should compare its surface brightness with the smoothed-out surface brightness of Virgo galaxies. In this case, we would have a substantially larger fraction. It is, however, difficult to derive a reliable value with our small sample. Since the inhomogeneous distribution seems to favor a local phenomenon, we take the value of \(\sim 10\%\). Under the assumption that the intracluster stellar population has the same mass-to-luminosity ratio as galaxies, \(M_{IC,\ast}\) in equation (1) is thus \(\sim 10\%\) of \(M_{gal}\).

Now, we proceed to the estimate of \(M_{gas}\) and the total gravitating mass, \(M_{total}\), to derive the baryonic fraction. Schindler et al. (1999) made a detailed analysis of smoothed-out distributions of galaxies and hot gas. They decomposed the distribution into three subclusters identified around M87, M86, and M49 (NGC4472). They present the density profile of the main M87 subcluster separately for hot gas, galaxies and total gravitating mass (their Fig.11b). We read from their plot the relative contribution of respective components at the position of our field as \(\rho_{total} : \rho_{gas} : \rho_{gal}=60:8:3\)\(^4\)

At the position of our field which is closer to M86, the contribution to \(\rho_{gal}\) from the M86 subcluster is 2.2 times that from the M87 subcluster (their Fig. 6)\(^5\). They found a compact X-ray halo around M86 subcluster. It is, however, interpreted as interstellar matter stripped

\(^4\) We use density instead of mass hereafter.

\(^5\) Contribution from the M49 subcluster is negligible since our field is far off the subcluster.
from M86 by ram pressure. If this is the case, the gas is already counted as $\rho_{\text{gal}}$. Accordingly, we do not increase $\rho_{\text{gas}}$ due to the M86 halo. We adopt a constant mass-to-light ratio of $(M/L)_B=10$ (e.g., Gerhard et al. 2001) for all the galaxies instead of 20 adopted by Schindler et al. (1999). This halves the value of $\rho_{\text{gal}}$ with respect to other components. Finally, we have $\rho_{\text{total}} : \rho_{\text{gas}} : \rho_{\text{gal}} = 60 : 8 : 4.8 = (3+2.2\times3)/2$.

With the contribution from the intracluster stellar population estimated here, we have

$$\rho_{\text{total}} : \rho_{\text{gas}} : \rho_{\text{gal}} : \rho_{\text{IC}} = 60 : 8 : 5 : 0.5$$

for the relative contribution, though $\rho_{\text{IC}}$ has a relatively large uncertainty. Therefore, if this field in the Virgo core is typical for the whole cluster, about a half ($=5.5/13.5$) of the baryons associated with the cluster formed stars, and the fraction of baryonic matter is about 18% ($=13.5/73.5$). With the value $\Omega_b = 0.02$ for $h = 0.7$ (e.g., Fukugita et al. 1998), we obtain $\Omega_{\text{total}} \simeq 0.11 (=0.02/0.18)$ for total gravitating mass.

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8
pixels. 2)
Table 3. Candidates for ICPNe in the Virgo cluster.

| ID  | α (J2000) | δ    | m(5007) | [OIII] r(Kron) | Hα (V + R) | [OIII]-(V + R) | [OIII]-Hα | Notes |
|-----|-----------|------|---------|---------------|------------|----------------|-----------|-------|
| I-1 | 12:26:51.16 | 12:48:44.2 | 27.269 | 0.969 | 2.618 | 1.995 | -1.989 | 2.958 | -1.026 |
| I-2 | 12:26:50.95 | 12:49:48.4 | 27.193 | 0.893 | 2.440 | 3.094 | 5.000 | -4.107 | -2.200 |
| I-3 | 12:26:36.70 | 12:54:12.0 | 26.700 | 0.400 | 2.801 | 1.141 | -0.075 | 0.475 | -0.741 |
| I-4 | 12:26:36.47 | 12:54:21.3 | 26.891 | 0.591 | 2.187 | 1.820 | -1.759 | 2.351 | -1.229 |
| I-5 | 12:26:33.35 | 12:54:56.6 | 27.269 | 0.969 | 2.292 | 2.780 | 5.000 | -4.031 | -1.811 |
| I-6 | 12:26:30.50 | 12:51:26.5 | 27.100 | 0.800 | 2.320 | 1.512 | 5.000 | -4.200 | -0.711 |
| I-7 | 12:26:32.26 | 12:54:09.0 | 26.700 | 0.400 | 2.801 | 1.141 | -0.075 | 0.475 | -0.741 |
| I-8 | 12:26:20.71 | 12:38:26.2 | 26.389 | 0.089 | 2.099 | 2.209 | -1.343 | 1.432 | -2.120 |
| I-9 | 12:26:19.57 | 12:34:10.0 | 26.677 | 0.377 | 2.781 | 2.088 | -2.634 | 3.011 | -1.710 |
| I-10 | 12:26:34.35 | 12:54:56.6 | 27.269 | 0.969 | 2.292 | 2.780 | 5.000 | -4.031 | -1.811 |
| I-11 | 12:25:46.03 | 12:54:14.8 | 27.207 | 0.907 | 2.137 | 1.587 | 5.000 | -4.093 | -0.680 |
| I-12 | 12:25:42.95 | 12:51:08.6 | 27.185 | 0.885 | 1.867 | 2.237 | 5.000 | -4.598 | -1.835 |
| Notes: 1) Kron half light radius is in units of pixels. 2) confirmed spectroscopically. 3) spectroscopy unsuccessful. |
**Fig. 1.** Coadded [OIII] image of the 34′ × 27′ survey field. ICPNe candidates are marked by the circles. The lower left area bounded by the black line indicates the area excluded from our survey because of the dead CCD chip. The margin of the field where S/N is low is also excluded. Envelopes of bright galaxies are subtracted as much as possible for the detection of PNe embedded there.

**Fig. 2.** Finding chart of the 38 ICPNe candidates ([OIII] image). An area 1′ × 1′ is shown. North is up, and east is to the left.
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