Intracluster Planetary Nebulae in the Virgo Cluster
I. Initial Results

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ABSTRACT

We report the initial results of a survey for intracluster planetary nebulae in the Virgo Cluster. In two $16' \times 16'$ fields, we identify 69 and 16 intracluster planetary nebula candidates, respectively. In a third $16' \times 16'$ field near the central elliptical galaxy M87, we detect 75 planetary nebula candidates, of which a substantial fraction are intracluster in nature. By examining the number of the planetaries detected in each field and the shape of the planetary nebula luminosity function, we show that 1) the intracluster starlight of Virgo is distributed non-uniformly, and varies between subclumps A and B, 2) the Virgo Cluster core extends $\sim 3$ Mpc in front of M87, and thus is elongated along the line-of-sight, and 3) a minimum of 22% of Virgo's stellar luminosity resides between the galaxies in our fields, and that the true number may be considerably larger. We also use our planetary nebula data to argue that the intracluster stars in Virgo are likely derived from a population that is of moderate age and metallicity.

Subject headings: planetary nebulae: general — galaxies: intergalactic medium — galaxies: interactions — clusters: individual: Virgo

1. Introduction

The concept of intracluster starlight was first proposed by Zwicky (1951), when he claimed to detect excess light between the galaxies of the Coma cluster. Follow-up photographic searches for intracluster luminosity in Coma and other rich clusters (Welch & Sastry 1971; Melnick,
White, & Hoessel 1977; Thuan & Kormendy 1977) produced mixed results, and it was not until the advent of CCDs that more precise estimates of the amount of intracluster starlight were made (cf. Guldeheus 1989; Uson, Boughn, & Kuhn 1991; Viche-Gómez, Pelló, & Sanahuja 1994; Bernstein et al. 1995). All these studies suffer from a fundamental limitation: the extremely low surface brightness of the phenomenon. Typically, the surface brightness of intracluster light is less than 1% that of the sky, and measurements of this luminosity must contend with the problems presented by scattered light from bright objects and the contribution of discrete sources below the detection limit. Consequently, obtaining detailed information on the distribution, metallicity, and kinematics of intracluster stars through these types of measurements is extremely difficult, if not impossible.

An alternative method for probing intracluster starlight is through the direct detection and measurement of the stars themselves. Recent observations have shown this to be possible. In their radial velocity survey of 19 planetary nebulae (PN) in the halo of the Virgo Cluster galaxy NGC 4406 (M86), Arnaboldi et al. (1996) found 3 objects with $v > 1300 \text{ km s}^{-1}$; these planetaries are undoubtably intracluster in origin. Similarly, Ferguson, Tanvir, & von Hippel (1998) detected Virgo’s intracluster component via a statistical excess of red star counts in a Hubble Space Telescope (HST) Virgo field over that in the Hubble Deep Field. Finally, intracluster stars have been unambiguously identified from the ground via planetary nebula surveys in Fornax (Theuns & Warren 1997) and Virgo (Méndez et al. 1997; Ciardullo et al. 1998).

Motivated by these results, we have begun a large scale [O III] $\lambda 5007$ survey of intergalactic fields in Virgo, with the goal of mapping out the distribution and luminosity function of intracluster planetary nebulae (IPN). Depending on the efficiency of tidal stripping, Virgo’s intracluster component is predicted to contain anywhere from 10% to 70% of the cluster’s total stellar mass (Richstone & Malumuth 1983; Miller 1983). A survey of several square degrees of Virgo’s intergalactic space with a four meter class telescope should therefore detect several thousand PN, and shed light on both the physics of tidal-stripping and on the initial conditions of cluster formation. Here, we present the first results of our survey.

2. Observations and Reductions

On 1997 March 6-9 and 16, we imaged the Virgo Cluster through a 44 Å wide redshifted [O III] $\lambda 5007$ filter (central wavelength, $\lambda_c = 5027$ Å) and a 267 Å wide off-band filter ($\lambda_c = 5300$ Å) with the prime focus camera of the Kitt Peak 4-m telescope and the T2KB 2048 $\times$ 2048 Tektronix CCD. In this initial survey, three $16' \times 16'$ fields were chosen for study: one located at the isopleth center of Virgo subclump A approximately 52' north and west from M87, one $\sim 34'$ north and east of the giant elliptical NGC 4472 in subclump B, and one $\sim 13' 8$ north of M87, also in subclump A (For the definitions of the subclumps, see Binggeli, Tammann, & Sandage 1987). The conditions during the bulk of the observations were variable in both seeing and transparency. However, at least one image of each field was taken on the photometric nights of 1997 Mar 8 and 9. These photometric
images served to calibrate the remaining frames, and allowed us to put all our measurements on a standard system.

The exact coordinates of the field centers, as well as a summary of the observations appear in Table 1. Figure 1 displays the locations of our three fields, along with the locations of other detections of Virgo’s intracluster stars: M86 (via PN spectroscopy; Arnaboldi et al. 1996), M87 (via PN imaging; Ciardullo et al. 1998), an HST Virgo field (via excess red star counts; Ferguson, Tanvir, & von Hippel 1998), and a blank Virgo field observed with the William Hershel Telescope (via PN imaging; Méndez et al. 1997).

Our survey technique was as described in Jacoby et al. (1989) and Ciardullo, Jacoby, & Ford (1989b). Planetary nebula candidates were identified by “blinking” the sum of the on-band images against corresponding off-band sums, and noting those point sources which were only visible in [O III]. This procedure netted 76 planetary nebula candidates in Field 1, 16 PN in Field 2, and 75 in Field 3. The magnitudes of the IPN were then measured relative to bright field stars via the IRAF version of DAOPHOT (Stetson 1987), and placed on a standard system by comparing large aperture measurements of field stars on the Mar 8 and 9 images with similar measurements of Stone (1977) standard stars. Finally, monochromatic fluxes for the PN were computed using the techniques outlined in Jacoby, Quigley, & Africano (1987), Jacoby et al. (1989) and Ciardullo, Jacoby, & Ford (1989b). These were converted to $m_{5007}$ magnitudes using:

$$m_{5007} = -2.5 \log F_{5007} - 13.74$$

where $F_{5007}$ is in units of ergs cm$^{-2}$ s$^{-1}$.

We note here that our $m_{5007}$ magnitudes carry an additional uncertainty which is unique to IPN photometry. In order to compare the monochromatic flux of an emission line object with the flux of a continuum source (i.e., a standard star), the transmission of the filter at the wavelength of the emission line must be known relative to its total integrated transmission (cf. Jacoby, Quigley, & Africano 1987). For PN observations within other galaxies, this quantity is known (at least, in the mean) from the recessional velocity and velocity dispersion of the target galaxy. However, for our intergalactic PN survey, we do not know a priori what the kinematic properties of the target objects are, and hence we do not know the mean wavelength of their redshifted [O III] $\lambda 5007$ emission lines. In deriving our monochromatic [O III] $\lambda 5007$ magnitudes, we have assumed that the velocity dispersion of the intracluster PN follows that of the Virgo Cluster as a whole (cf. Binggeli, Sandage, & Tammann 1985), but this may not be true. Although the systematic error introduced by this uncertainty is small ($\sim 5\%$), the effect may be important for individual objects.
2.1. Obtaining a Statistical Sample

Before we can compare the numbers and luminosity functions of IPN, we must first determine the photometric completeness limit in each field, and define a statistical sample of objects. Because our data were taken in mostly blank fields, our ability to detect IPN was not a strong function of position. We therefore used the results of Jacoby et al. (1989) and Hui et al. (1993) and equated our limiting magnitude for completeness with a signal-to-noise of 9. This is approximately the location where the PNLF (which should be exponentially increasing at the faint end) begins to turn down. The relative depth of each field derived in this way also agrees with that expected from measurements of the seeing and mean transparency on the individual images.

In addition to excluding faint sources, we must make another modification to the IPN luminosity function. Any galaxy that is within, or adjacent to our data frames, can potentially contaminate our IPN sample with PN still bound to their parent galaxies. Because PN are relatively rare objects, this source of contamination is unimportant for the small, low luminosity, dwarf galaxies that are scattered throughout the Virgo Cluster. However, PN in the halos of bright galaxies can be mistaken for intracluster objects, and must be taken into account.

In Fields 1 and 2, there is only one contaminating object of any consequence, NGC 4425, a relatively bright \((0.2L^\ast)\) lenticular galaxy on the extreme western edge of Field 1. From numerous observations (examples include [Jacoby, Ciardullo, & Ford 1990; Ciardullo et al. 1989a]), PN very closely follow the spatial distribution of galaxy starlight. We therefore used surface photometry measurements to exclude seven of our PN candidates that fell within 2.4′ of NGC 4425’s nucleus. From the \(B\)-band surface photometry of Bothun & Gregg (1990), this distance corresponds to approximately five effective radii or seven disk scale lengths. Without these objects, we have 69 and 16 IPN candidates in Fields 1 and 2, respectively, and a total of 44 and 9 objects in the photometrically complete samples.

For Field 3, which has a total of 47 objects in its photometrically complete sample, the situation is more complex. Because the field is only 13.8′ from the center of M87, some fraction of the objects in this region are probably bound to the galaxy. The angular distribution of the 75 planetary candidates does roughly follow the gradient defined by the M87 surface brightness measurements of Caon, Capaccioli, & Rampazzo (1990), and this does suggest an association with the galaxy. However, these data, by themselves, do not exclude the possibility that a large fraction of our PN are intracluster in origin. Indeed, since intracluster stars contribute luminosity just as galactic stars do, it is difficult to distinguish intracluster light from galactic light from surface photometry alone. The situation is further complicated by the recent discovery of an extremely large, highly elongated, low surface brightness halo which surrounds M87 and extends \(\sim 15′\) on the sky (Weil, Bland-Hawthorn, & Malin 1997). This structure is so large, that it is probably not all bound to the galaxy. The complexity of the region makes it impossible to determine the precise number of galactic PN contaminating the intracluster counts of Field 3 using surface photometry. We will return to this issue in §3 below.
We note that there is one other possible source of contamination to our intracluster PN sample. Any object that emits a large amount of flux in our redshifted $\lambda 5007$ filter, but is undetectable in the offband filter will be mistaken for a planetary nebula. Thus, distant objects, such as gas-rich starburst galaxies or quasars, could have enough flux in a redshifted emission line to be detected in our survey. In practice, however, this is extremely unlikely. The emission lines of importance are \([\text{O II}]\) $\lambda 3727$ at $z \sim 0.35$ and Ly$\alpha$ at $z \sim 3.1$. From surveys of high-redshift quasars (Schmidt, Schneider, & Gunn 1995), we should expect much less than one $z = 3.1$ bright quasar in our three fields combined. Additionally, since our PN candidates have point-like point-spread-functions, those $z \sim 0.35$ galaxies with linear extents greater than $\sim 10$ kpc should have all been excluded on the basis of their angular size. These and similar arguments made by other authors (Theuns & Warren 1997; Méndez et al. 1997), imply that contamination from background sources is probably not significant in our survey.

The final luminosity functions for our 3 fields are plotted in Figure 2. For comparison, a sample of suspected intracluster PN’s from M87’s inner halo (Ciardullo et al. 1998) are also plotted.

3. The Distribution of Intracluster Stars

The most obvious feature displayed in Figure 2 is the dramatically different numbers of IPN in Fields 1 & 2. Although the survey depths of the three regions differ (due to differences in sky transparency and seeing), it is clear that the density of intracluster objects in Field 1 at the center of subclump A is much larger than that in Field 2. After accounting for the different depths, the PN density in Field 3, near M87, is smaller by a factor of at least two, and the number of PN in Field 2, which is near the edge of the 6 degree Virgo Cluster core in subclump B, is down by a factor of $\sim 4$. This behavior is quite intriguing.

The fact that subclump B has fewer PN than subclump A can probably be attributed to cluster environment. It is well known that subclump B has fewer early-type galaxies than subclump A (Binggeli, Tammann, & Sandage 1987). If ellipticals and intracluster stars have a related formation mechanism (i.e., galaxy interactions), then a direct correlation between galaxy type and stellar density in the intergalactic environment might be expected.

What is harder to understand is the high IPN density in Field 1. Although galaxy isopleths place the Virgo Cluster center in Field 1 (Binggeli, Tammann, & Sandage 1987), X-ray data clearly demonstrate that the true center of the cluster is at M87 (Böhringer et al. 1994). The reason for the offset is a subcluster of galaxies associated with M86. Kinematic data (Binggeli, Popescu, & Tammann 1993) and ROSAT X-ray measurements (Böhringer et al. 1994) both show that the center of Virgo subclump A is contaminated by a separate group of galaxies which is falling in from the far side of the cluster. This interpretation is confirmed via direct distance measurements using the planetary nebula luminosity function (Jacoby, Ciardullo, & Ford 1990) and surface
brightness fluctuation method (Ciardullo, Jacoby, & Tonry 1993; Tonry et al. 1997): both place M86 $\sim$ 0.3 mag behind M87. At this distance, the PN associated with M86 and its surroundings should be beyond the completeness limit of our survey, and should not be contributing to our PN counts. The observed IPN density of Field 1 should therefore be smaller than that measured near M87, not greater.

A second feature of Figure 2 is the slow fall-off of the bright-end of Field 3's planetary nebula luminosity function (PNLF). Observations in $\sim$ 30 elliptical, spiral, and irregular galaxies have demonstrated that a system of stars at a common distance will have a PNLF of the form:

$$N(M) \propto e^{0.307M[1 - e^{3(M^* - M)}]}$$

(2)

where $M^* \approx -4.5$ (Jacoby et al. 1992). In no isolated galaxy has the PNLF ever deviated from this form. However, in a cluster environment such as Virgo, the finite depth of the cluster can distort the PNLF, as PN at many different distances contribute to the observed luminosity function. Due to the lack of survey depth in Field 1, and small number of PN in Field 2, we cannot determine whether the PNLFs of these fields differ from the empirical function. However the PNLF of Field 3 is clearly distorted, in the manner identical to that found by Ciardullo et al. (1998) in their survey of the envelope of M87.

Figure 3 illustrates this effect in more detail. In the figure, we first compare the observed PNLF of Field 3 to the most likely empirical curve (solid line) as found via the method of maximum likelihood (Ciardullo et al. 1989a). The fit is extremely poor, and a Kolmogorov-Smirnov test rejects the empirical law at the 93% confidence level. The reason for the poor fit is simple: the presence of bright, “overluminous” objects forces the maximum-likelihood technique to find solutions which severely overpredict the total number of bright PN in the field.

There is only one plausible hypothesis for the distorted PNLF and the overabundance of bright PN — the presence of intracluster objects. An instrumental problem is ruled out, since the bright-end distortion has also been seen in data taken of M87's envelope two years earlier with a different filter and under different observing conditions (Ciardullo et al. 1998). Similarly, extreme changes in metallicity cannot explain the discrepancy. Unless the bulk of the intracluster stars are super metal-rich ([O/H] $\gtrsim$ 0.5), abundance shifts can only decrease the luminosity of the [O III] $\lambda$5007 line, not increase it (Dopita, Jacoby, & Vassiliadis 1992; Ciardullo & Jacoby 1992). Finally, neither population age nor the existence of dust is a likely scenario: the former requires an unreasonably young ($< 0.5$ Gyr) age for M87's stellar envelope (Dopita, Jacoby, & Vassiliadis 1992; Méndez et al. 1993; Han, Podsiałdowski, & Eggleton 1994), and the latter implies a significant gradient in foreground extinction between 2 and 7 effective radii from M87's center.

Thus, one is left with the hypothesis, first presented by Jacoby (1996) and Ciardullo et al. (1998), that intracluster PN are responsible for the distorted PNLF. From our own study, and that of others (Arnaboldi et al. 1995; Méndez et al. 1997; Ferguson, Tanvir, & von Hippel 1998), it is clear that a significant fraction of intracluster stars exist in Virgo, and some of these stars should be positioned in front of M87 along the line-of-sight. The existence of foreground PN naturally
explains the existence of “overluminous” PN, and is supported by the fact that the brightest PN in Field 3 are of comparable magnitude to the brightest objects found in the Ciardullo et al. (1998) survey of M87.

The distorted PNLF gives us a way to estimate a lower limit to the number of IPN in Field 3. To do this, we plot a dashed line in Figure 3, which represents the expected luminosity function of M87 planetaries using the observed PNLF distance modulus of the inner part of the galaxy \((m - M = 30.87; \text{Ciardullo et al. 1998})\). To normalize this curve, we assume that all the PN at \(m_{5007} = 26.9\) belong to the galaxy. As is illustrated, there is an excess of bright objects compared to that expected from M87 alone: these are objects at the bright end of the intracluster planetary nebula population. If we statistically subtract the M87 luminosity function from the Field 3 data, we arrive at the conclusion that at least 10 ± 2 planetaries with \(m_{5007}\) brighter than 26.5 are intracluster in nature, where the uncertainty is solely due to the uncertainty in the normalization value.

Note that this estimate is a bare minimum for the number of intracluster PN. For all reasonable planetary nebula luminosity functions, there are many more faint PN than bright PN. Thus, our assumption that all \(m_{5007} = 26.9\) PN are galactic is clearly wrong. However, without some model for the distribution of intracluster stars, the shape of the intracluster PNLF cannot be determined. This makes it impossible to photometrically distinguish faint intracluster PN from PN that are bound to M87. For the moment, we therefore conservatively claim that at least 10 ± 2 intracluster planetaries are present in Field 3. In the future, it should be possible to refine this estimate with improved observations of the precise shape of the PNLF, and with the use of dynamical information obtained from PN radial velocity measurements.

A final feature of Figure 2, and perhaps the most remarkable, deals with distance. Even a cursory inspection of Figure 2 shows that the IPN of Field 1 are significantly brighter than those of Field 2. If we fit the two distributions to the PNLF of equation (2) via the technique of maximum likelihood (Ciardullo et al. 1989a), then the most likely distance to the PN of Field 1 is 11.8 ± 0.7 Mpc, while that for Field 2 is 14.7 ± 1.5 Mpc. The fact that Field 2 is more distant is not surprising, since both Yasuda, Fukugita, & Okamura (1997) and Federspiel, Tammann, & Sandage (1997) place the galaxies of subclump B ∼ 0.4 mag behind those of subclump A. What is surprising is the relatively small distance to the IPN of Field 1. Most modern distance determinations, including the analysis of Cepheids in spirals by van den Bergh (1996) and the measurement of the planetary nebula luminosity function and surface brightness fluctuations in ellipticals (Jacoby, Ciardullo, & Ford 1990; Tonry et al. 1997), place the core of the Virgo Cluster at a distance of between 14 and 17 Mpc. No modern measurement to Virgo gives a distance smaller than ∼ 14 Mpc, and 11.8 Mpc is certainly not a reasonable value for the distance to the cluster.

The reason for the ∼ 3 Mpc discrepancy is that the PNLF law has an extremely sharp cutoff at the bright end of the luminosity function. As a result, our PN detections are severely biased
towards objects on the front edge of the cluster, and our distance estimates carry the same bias. Our derived value of 11.8 Mpc therefore represents the distance to the front edge of the Virgo Cluster, not the distance to the galaxies in the Virgo Cluster core.

Another way of looking at the data is to consider the brightest IPN in Fields 1 and 3. If we assume that these bright objects are indeed part of the Virgo Cluster and have an absolute magnitude near $M^*$, then their apparent magnitudes yield an immediate upper limit to the front edge of each field. The result is that the brightest IPN of Fields 1 and 3 have distances of no more than 11.7 Mpc, i.e., they are $\sim 3$ Mpc in front of the cluster core, as defined by the original PNLF measurements of Jacoby, Ciardullo, & Ford (1990). The same conclusion was reached by Ciardullo et al. (1998) using the sample of PN around M87’s inner halo. This distance is significantly larger than the size of the cluster projected on the sky: at a distance of $\sim 15$ Mpc, the classical 6 degree core of Virgo translates to a linear extent of only $\sim 1.5$ Mpc. Although it is unclear how our measurement of cluster depth quantitatively compares to the classical angular estimate of the core (Shapley & Ames 1926; see the discussion in de Vaucouleurs & de Vaucouleurs 1973), our data does suggest that Virgo is elongated along our line-of-sight, perhaps by as much as a factor of two.

It is worth repeating here that the planetary nebula luminosity function is extremely insensitive to the details of its parent population, and those dependences that do exist cannot explain the bright apparent magnitudes seen in the IPN population. The problem is more fully discussed in Ciardullo et al. (1998), but, in summary, there is no reasonable explanation for the existence of these bright [O III] $\lambda$5007 sources other than that their location is in the foreground of the Virgo Cluster. We note that many authors have suggested that the Virgo Cluster has substantial depth (for example, see the galaxy measurements of Pierce & Tully 1988; Tonry, Ajhar, & Luppino 1990; Yasuda, Fukugita, & Okamura 1997), but this direct measurement is still quite surprising.

### 4. The Stellar Population and Total Number of Intracluster Stars

Renzini & Buzzoni (1986) have shown that 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, then every stellar system should have $\alpha \sim 50 \times 10^{-8}$ PN-$L_\odot^{-1}$. Observations in elliptical galaxies and spiral bulges have shown that no galaxy has a value of $\alpha$ greater than this number, but $\alpha$ can be a up to a factor of five smaller (Ciardullo 1995). Nevertheless, the direct relation between number of planetary nebulae and parent system luminosity does provide us with a tool with which to estimate the number of stars in Virgo’s intergalactic environment.

In order for us to estimate the density of intracluster stars in Virgo, we must first fit the observed PNLF with a model which represents the distribution of planetary nebulae along the line-of-sight. Such a model is a necessary step in the analysis: as seen above, Virgo’s intracluster
component extends \( \sim 0.5 \) mag in front of its core, and thus our sample of PN is severely biased towards objects on the near side of the cluster. To investigate the effect of this bias, we considered two extreme models for the distribution of Virgo’s intrachuster stars: a single component model, in which all the PN are at a common distance, and a radially symmetric model, in which the intrachuster stars are distributed isotropically throughout a sphere of radius 3 Mpc. The symmetric model was then adjusted to deliver a “best fit” to the observed PNLF at the assumed cluster distance of 15 Mpc (Jacoby, Ciardullo, & Ford 1990). For the single component models, we adopted the distances derived in §3. The most likely value for the underlying population’s stellar luminosity was then calculated using the method of maximum likelihood (Ciardullo et al. 1989a) and an assumed value of \( \alpha_{2.5} = 20 \times 10^{-9} \), which is an average value for elliptical galaxies (\( \alpha_{2.5} \) is the number of PN within 2.5 mag of \( M^* \) per unit bolometric luminosity). Because of our limited knowledge of the luminosity function of Field 3, we used single component models only for this field, assuming that field contains 10 IPN within our completeness limit. In addition, because of the very large uncertainties in the above models, we also computed a single component model using \( \alpha_{2.5} = 50 \times 10^{-9} \) PN-\( L^{-1} \odot \); this last model represents the minimum amount of intrachuster starlight necessary to be consistent with our data. The results of our models are summarized in columns 1-4 in Table 2.

The total amount of intrachuster starlight found is quite large, at least \( 6.8 \times 10^9 \) \( L_\odot \) in the 768 square arcminutes we surveyed, and probably much more. As expected, the density of intrachuster stars varies significantly between the fields. For Fields 1 and 2, the choice of cluster model changes the amount of derived intrachuster light dramatically. In the single component model, most of the PN can be on the near side of the cluster, where we can see objects relatively far down the luminosity function. In this scenario, the size of the IPN’s parent population is relatively small, as is the amount of intrachuster light. In contrast, the symmetric model places a large number of stars on the back side of the cluster, where they contribute light, but do not populate the bright end of the PN luminosity function. The intrachuster luminosity in this picture is correspondingly larger.

How likely is it that the intrachuster stars are distributed symmetrically in the cluster? There is strong evidence to suggest that neither the galaxies nor the intrachuster stars are in virial equilibrium. Based on the distribution and kinematics of galaxies, Bingelli, Tammann, & Sandage (1987) and Bingelli, Popescu, & Tammann (1993) concluded that the core of Virgo exhibits a significant amount of substructure. Similarly, Ciardullo et al. (1998) showed that the PNLF of intrachuster stars near M87 is incompatible with that of a relaxed system. Although these analyses do not formally exclude all symmetric distributions, they do suggest that a symmetric distribution is unlikely.

Although our limited amount of photometric data do not allow us to address the question of Virgo’s structure directly, we can gain some insight into the state of the intrachuster stars by speculating about their likely origin. To do this, we first focus on the metallicity of the observed IPN. Many of the planetary nebulae detected in our survey are extremely bright: some are more
than 0.6 mag brighter than $m^*$ at the center of the cluster. In §3, we interpreted this brightness in terms of distance, and were thus able to place the IPN $\sim 3$ Mpc in front of M87. This argument, however, assumes that $M^*$, the absolute magnitude of the PNLF cutoff, is well known. For most stellar populations, this is a good assumption, as evidenced by the agreement between PNLF distances and distances determined from other methods (cf. Jacoby et al. 1992; Ciardullo, Jacoby, & Tonry 1993; Feldmeier, Ciardullo, & Jacoby 1997). However, in extremely metal poor systems, the decreased number of oxygen atoms present in a PN's nebula does have an affect. Specifically, PN from a population whose metallicity is one-tenth solar are expected to have a value of $M^*$ that is fainter than the nominal value by more than 0.25 mag (Ciardullo & Jacoby 1992; Dopita, Jacoby, & Vassiliadis 1992; Richer 1994). This increase in $M^*$ translates directly into an error in distance. For example, if the intracluster environment of Virgo were filled with stars with one-tenth solar abundance, our derived distance to the front of the cluster would be overestimated by $\sim 11\%$, and our value for the distance between the front of the cluster and the Virgo core galaxies would be underestimated by almost 50%. Note, however, that we already measure a Virgo Cluster depth that is $\sim 2$ times that of its projected size; lowering the metallicity of the stars would only increase this ratio. It therefore seems likely that the PN detected in our survey are of moderate metallicity.

Similarly, the mere fact that we do see a large number of IPN suggests that most of the intergalactic stars are not extremely old. In their [O III] $\lambda 5007$ survey of Galactic globular clusters, Jacoby et al. (1997) found a factor of $\sim 4$ fewer PN than expected from stellar evolution theory. Jacoby et al. attribute this small number to the extreme age of the stars. Observations in the Galaxy suggest that stars with turnoff masses of $\sim 0.8 M_\odot$ produce post asymptotic giant branch stars with extremely small cores, $M_c < 0.55 M_\odot$ (Weidemann & Koester 1983). Objects such as these evolve to the planetary nebula phase very slowly: so slowly, in fact, that their nebulae can diffuse into space before the stars become hot enough to produce a significant number of ionizing photons. If this scenario is correct, then the fact that we see large numbers of IPN indicates that the intracluster stars of Virgo cannot be as old as the globular cluster stars of the Galaxy.

If the intracluster stars of Virgo are, indeed, of moderate age and metallicity, then they must have been stripped out of their parent galaxies at a relatively recent epoch. One likely way of doing this is through “galaxy harassment” whereby high-speed encounters between galaxies rip off long tails of matter which lead and follow the galaxy (Moore et al. 1996). Although this tidal debris will eventually dissolve into the intracluster environment, it is possible that the increased energy of these stars may cause them to linger in the outer parts of the cluster for a long time. It is therefore possible that the intergalactic environment of Virgo is not a homogeneous region, but is instead clumpy, and filled with filaments. It may be that the bright PN present in Field 1 belong to one such structure that happens to be in the front side of the cluster. If this is correct, the symmetric model for Field 1 should be a gross overestimate of the true amount of intracluster starlight.

If we assume that the intracluster stars come from an old stellar population, similar to that
found in M87 with a $B-V$ color of 1.0 (de Vaucouleurs et al. 1991), a bolometric correction of $-0.85$ (Jacoby, Ciardullo, & Ford 1990), and a mean distance of 15 Mpc, then the luminosities implied by our PN observations can be expressed in terms of $B$-band surface brightnesses. Although the values are position and model dependent (cf. Table 2, column 5), the result is quite interesting. Our PN observations imply that the surface brightness in the Virgo Cluster core varies between $B \sim 26$ and $B \sim 30$ mag per sq. arcsec. These values are in excellent agreement with other PN-derived surface brightness values in Virgo (Méndez et al. 1997) and Fornax (Theuns & Warren 1997). They are, however, significantly larger than the value of $B \sim 31.2$ implied from red star counts on HST frames (Ferguson, Tanvir, & von Hippel 1998). One possible explanation for this discrepancy lies in the locations of the fields: the HST field is 50′ east of M87, whereas Fields 1 and 2 are in denser regions of the cluster. If intracluster stars are concentrated towards the cores of the subclumps of Virgo, then the low number of red stars observed by HST may be attributable to the field’s location. Under this assumption, and using the same stellar population model used by Ferguson, Tanvir & von Hippel (1998), we would expect only $\sim 5$ IPN brighter than $m_{5007} = 27.0$ in a $16′ \times 16′$ field centered on the HST position.

On the other hand, our fields may, indeed, be typical locations in the Virgo Cluster. As described above, the high galaxy density in Field 1 is due, in part, to objects on the far side of the cluster which do not contribute to the observed sample of planetaries. Similarly, the shape of the PNLF of Field 3 suggests that much of the intracluster luminosity in that region is not associated with the physical core of Virgo, but is only present in the field through projection.

If our survey regions are typical of Virgo in general, then we can use our observations to estimate the total fraction of Virgo’s starlight which is between the galaxies. By fitting the surface distribution of Virgo galaxies in subclump A to a King model with core radius 1.7, Binggeli, Tammann, & Sandage (1987) derived a central luminosity density of the cluster of $1 \times 10^{11} L_\odot$ per square degree. If we scale this galactic luminosity density, which we denote as $L_{\text{galaxies}}$ (cf. Table 2, column 6), to the sizes and locations of Fields 1 and 3, we can directly determine the importance of intracluster starlight. Due to its irregularity, Binggeli, Tammann, & Sandage (1987) did not fit an analytical model to subclump B. However, the luminosity density in Field 2 is certainly not greater than that for Field 1. We therefore use Field 1’s value to set a lower limit on the fraction of intracluster starlight in Field 2. The results are given in column 7 of Table 2.

Depending on the model and the field, the fraction of intracluster light varies from 12% to 88% of the cluster’s total luminosity. To set a lower limit to the relative importance of intracluster starlight, we average the results from our three fields, using the smallest fraction found for each field. We find an average fraction of 22%. Similarly, to find the upper limit to the intracluster fraction, we average the largest fractions determined. In this case, we find an average fraction of 61%. This range is in rough agreement with the results derived from other PN observations in Virgo (Méndez et al. 1997) and Fornax (Theuns & Warren 1997). They also agree with the direct measurement of intracluster light in Coma (Bernstein et al. 1995).
We stress that these results are very uncertain, due to our lack of knowledge about the true distribution of intracluster stars, and the possible variation of $\alpha_{2.5}$. In addition, it is also probable that we have missed a small fraction of the IPN present in our fields due to the finite width of our interference filter. If the IPN velocity dispersion follows that of the galaxies, then $\sim 8\%$ of the IPN will be Doppler shifted out of the bandpass of our 44 Å full-width half-maximum filter. However, since the true kinematics of the IPN are unknown, this fraction cannot be determined precisely. Nevertheless, regardless of the particular model, a large fraction of intracluster stars are present in the Virgo Cluster.

The large amount of intracluster starlight found by this and other studies places new constraints on models of the formation and evolution of galaxy clusters. If, as we have suggested, the intracluster stars are of moderate age and metallicity, they must not have been formed in the intracluster environment, but instead have been removed from their parent galaxies during encounters. Therefore, the number and distribution of intracluster stars could be a powerful tool for discovering the history of individual galaxy clusters. Furthermore, since intracluster stars are already free of the potential wells of galaxies, they may contribute a significant fraction of metals and dust to the intracluster medium.

The large amount of intracluster stars is also an unrecognized source of baryonic matter that must be taken into account in studies of galaxy clusters. Though not enough to account for all of the dark matter, intracluster stars do increase the fraction of matter that is in baryonic form. This has potentially serious consequences for cosmological models. From their calculation of the baryon fraction in the Coma Cluster, White et al. (1993) found that their derived value was too large for the universe to simultaneously have $\Omega_0 = 1$ and also be in accord with calculations of cosmic nucleosynthesis. This result, sometimes called the “baryon catastrophe,” has been confirmed in several other galaxy clusters (White & Fabian 1995; Ettori, Fabian, & White 1997). Although the exact amount of intracluster starlight is currently very uncertain, the presence of a large number of intracluster stars can only increase the baryon discrepancy already found. More observations will be necessary to establish how much intracluster starlight adds to the observed baryon fraction of galaxy clusters.

5. Conclusion

We report the results of a search in three fields in the Virgo Cluster for intracluster planetary nebulae, and have detected a total of 95 intracluster candidates. From analysis of the numbers of the planetaries, we find that the amount of intracluster light in Virgo is large (at least 22% of the cluster’s total luminosity), distributed non-uniformly, and varies between subclump A and B. By using the planetary nebulae luminosity function, we derive an upper limit of $\sim 12$ Mpc for the distance to the front edge of the Virgo Cluster and use this to show that the cluster must be elongated along our line of sight. We also use the properties of planetary nebulae to suggest that the intracluster stars of Virgo have moderate age and metallicity. The large fraction of intracluster
stars found has potentially serious consequences for models of cluster formation and evolution, and for cosmological models. Finally, we note that this survey included less than 0.2% of the traditional 6 degree core of the Virgo Cluster. Many more intracluster planetary nebulae wait to be discovered.

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Fig. 1.— A 2.5 by 5.7 region of the Virgo Cluster, drawn from the Digitized Sky Survey. North is up, and east is to the left. Our three fields are indicated by the large squares of side 16′. Other detections of intracluster stars are also displayed including the intracluster planetary nebulae in front of M86 (Arnaboldi et al. 1996) and M87 (Ciardullo et al. 1998), intracluster red giant and asymptotic giant branch stars detected by the Hubble Space Telescope (Ferguson, Tanvir, & von Hippel 1998), and the intracluster planetary nebulae detected in the 4′ radius circular field of Méndez et al. (1997). The position of NGC 4472 is shown for reference.
Fig. 2.— The planetary nebula luminosity functions for the three intracluster fields, plus a sample of suspected intracluster planetaries from M87 (Ciardullo et al. 1998), binned into 0.2 mag intervals. The solid circles represent objects in our statistical IPN samples; the open circles indicate objects fainter than the completeness limit. Note that the numbers of intracluster planetaries vary from field to field, and that Field 2 appears to have a fainter cutoff than Fields 1 and 3.
Fig. 3.— The planetary nebula luminosity functions for Field 3, binned into 0.2 mag intervals. The solid circles represent objects in the statistical sample; the open circles indicate objects fainter than the completeness limit. The solid line shows the empirical planetary nebulae luminosity function shifted to the most likely distance modulus — it is excluded at the 93% confidence level. The dashed line is the planetary nebulae luminosity function placed at the best-fitting distance to M87 (Ciardullo et al. 1998), convolved with the photometric error function, and normalized to go through the point at $m_{5007} = 26.9$. The excess of ~10 planetaries at the bright end of the luminosity function demonstrates the presence of intracluster stars.
Table 1. Record of Observations

| Field | α(2000) | δ(2000) | Total Exposure Time (s) | Mean Transparency | Mean Seeing m<sub>5007</sub> completeness limit |
|-------|---------|---------|-------------------------|------------------|---------------------------------------------|
| 1     | 12 27 47.51 | 12 42 24.29 | 10800 | 78% | 1″1 | 26.4 |
| 2     | 12 29 49.54 | 8 34 22.35 | 18000 | 100% | 1″5 | 26.8 |
| 3     | 12 30 47.50 | 12 37 14.38 | 18000 | 98% | 1″4 | 27.0 |

Table 2. Model Results

| Field | Model | α<sub>2.5</sub> [10<sup>-9</sup> PN-L<sub>⊙</sub><sup>-1</sup>] | Implied Luminosity [×10<sup>9</sup>L<sub>⊙</sub> per field] | µ<sub>B</sub> | L<sub>galaxies</sub> [×10<sup>9</sup>L<sub>⊙</sub> per field] | Fraction |
|-------|-------|----------------------------------|---------------------------------|------|-----------------|---------|
| 1     | symmetric cluster | 20 | 55 | 25.5 | 7.1 | 88% |
| 1     | single component | 20 | 20 | 26.6 | 7.1 | 74% |
| 1     | single component | 50 | 5 | 28.1 | 7.1 | 41% |
| 2     | symmetric cluster | 20 | 15 | 27.0 | ≤ 7.1 | ≥ 68% |
| 2     | single component | 20 | 5 | 28.1 | ≤ 7.1 | ≥ 41% |
| 2     | single component | 50 | 1 | 29.9 | ≤ 7.1 | ≥ 12% |
| 3     | single component | 20 | 2 | 29.1 | 5.8 | 26% |
| 3     | single component | 50 | 0.8 | 30.1 | 5.8 | 12% |
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