

## Extragalactic Planetary Nebulae

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**Abstract.** Planetary nebulae (PNe) can be used to trace intermediate and old stellar populations in galaxies and the intracluster medium out to approximately 20 Mpc. PNe can be easily identified with narrow-band surveys, and their chemical abundances and radial velocities can be measured with multi-slit or multi-fiber spectrographs. We briefly review what has been accomplished to date, and include tables (with references) that summarize the observations of PNe in 42 galaxies and in the intracluster media of the Virgo and Fornax clusters. The surveys for intracluster PNe suggest that between 20% and 50% of the clusters' total stellar mass is in the intracluster medium! We illustrate the utility of PNe for dynamical studies by presenting results from a recently completed survey of Cen A (NGC 5128) with the NOAO mosaic camera on the CTIO 4-m telescope. The PNe and globular cluster surveys extend respectively to distances of 80 Kpc and 50 Kpc. We compare the kinematics of the stars in Cen A (736 PN velocities) to the kinematics of the red and blue globular clusters (188 clusters with measured velocities). The latter include 125 newly confirmed globular clusters from our survey.

### 1. Introduction

Planetary nebulae (PNe) can be used to trace old and intermediate-age stellar populations in galaxies and in the intracluster medium out to approximately 20 Mpc. Photometric and spectroscopic observations of PNe provide information about: 1) the stellar death rate, 2) the chemical composition of the planetaries' parent stars, 3) the distance to the galaxy, and 4) the stellar dynamics of the parent stellar population and the distribution of mass in the galaxy.

Planetary nebulae in the intracluster or intragroup medium (ICPNe) provide a measure of past tidal stripping and tidal disruption of galaxies within the cluster or group. Depending on the evolutionary state of the cluster, ICPNe may provide *thousands* of test particles that can be used to study the cluster's dynamics.

## 2. Identification of PNe and Camera/Telescopes Suitable for PNe Surveys

Planetary nebulae mark the endpoint of stellar evolution for stars with masses between  $\sim 0.8$  and  $8 M_{\odot}$  (Iben & Renzini, 1983; Dopita et al. 1997). The expanding shell (or shells) of a planetary nebula is ejected during the ascent of the asymptotic giant branch. The shell is ionized by the ultraviolet radiation from the newly exposed, hot helium-burning core. A large fraction of the radiation from the core, which has a luminosity equal to a red giant, is absorbed via ionization of hydrogen and helium, and converted into emission lines from the most abundant elements. The temperature of the nebula is set by equilibrium between heating from ionization and cooling from permitted and forbidden emission lines. Radiation from [OIII]  $\lambda 4959/5007$  is one of the most efficient cooling lines; the monochromatic luminosity in [OIII]  $\lambda 5007$  is comparable to the V-band luminosity of the K-giants in old stellar populations. Consequently, PNe can be efficiently identified by taking pairs of on-band and off-band [OIII]  $\lambda 5007$  images. When using ground-based telescopes, PNe in galaxies beyond the Magellanic Clouds will be unresolved, absent in the off-band image, and brighter in [OIII]  $\lambda 5007$  than  $H\alpha$ . Detailed descriptions of PNe survey techniques and issues that must be considered when selecting and buying interference filters can be found in Ford et al. (1989) and Jacoby et al. (1992).

Telescope and camera combinations that are particularly suitable for PNe surveys are summarized in Table 1. Column five gives the product of the telescope’s aperture times the field of view,  $A \times \Omega$ , normalized to the Subaru telescope’s “Suprime” camera. All else being equal (seeing and camera throughput),  $A \times \Omega$  is a figure of merit for a camera/telescope’s survey capability. The last column gives the distance at which a PN one magnitude fainter than the brightest PN will have a signal-to-noise ratio of 10 in the sum of four 2250 second exposures. We assumed that the seeing is  $0.75''$  FWHM, the net atmosphere/telescope/camera throughput is 0.5, the readnoise is  $6 e^-$  RMS per pixel, and the sky brightness and isophotal galaxy brightness are  $V = 22 \text{ mag}/\square''$ . For the MMT we assumed that the sky and galaxy surface brightnesses are 21.8, and that the CCDs are binned  $3 \times 3$  before readout.

Table 1. Telescopes and Cameras That Are Suitable for PNe Surveys

Telescope	Camera Format	Pixel Size (")	FOV (arc-min)	$A \times \Omega$	Dist (Mpc)
WHT 4.2-m/PNS	2k $\times$ 2k	0.33 $\times$ 0.30	11.3 $\times$ 10.3	0.045	20
ESO 2.2-m	8k $\times$ 8k	0.24	34 $\times$ 33	0.12	14
CTIO 4-m	8k $\times$ 8k	0.27	36 $\times$ 36	0.45	20
MMT 6.5-m	18k $\times$ 18k	0.08	24 $\times$ 24	0.66	25
CFHT 3.6-m	20k $\times$ 18k	0.18	62 $\times$ 56	0.97	18
Subaru 8.2-m	10k $\times$ 18k	0.20	30 $\times$ 24	1	29

The Planetary Nebula Spectrograph (PNS) (Arnaboldi et al. 2001; Douglas, 2001) on the William Herschel Telescope is a slitless spectrograph preceded by a narrow band [OIII]  $\lambda 5007$  filter. The spectrograph is rotated  $180^\circ$  between exposures. When the images are compared, PNe will be pairs of stellar sources

whose separations are proportional to their radial velocities, whereas stars will be dispersed into short spectra. The PNS will be very effective for measuring the radial velocities of PNe for two reasons. When the seeing is very good, as frequently is the case on the WHT (Wilson et al. 1999), the effective slit will be the seeing FWHM. And, a second observing run is not required to measure the radial velocities.

The Hubble Advanced Camera for Surveys will be able to detect ICPNe one magnitude fainter than the brightest PN at a distance of  $\sim 200$  Mpc when the sky is as faint or fainter than 23.2 V-mag/ $\square''$ .

### 3. Abundance Determinations Using PNe

Spectroscopic observations of planetary nebulae are presently the only way to measure the chemical abundances of individual elements in old and intermediate age stars at distances of  $\sim 1$  Mpc or greater. Although the nebular abundances of He, C, N, and S are enhanced by nucleosynthesis in the parent star (e.g. Dopita et al. 1997), comparisons can be made of relative abundances from one part of a galaxy to another, and between galaxies.

In the LMC, [O/H] in bright PNe has the same value as [O/H] in HII regions (Richer 1993); consequently, the oxygen abundance measured in PNe is a good measure of the oxygen abundance in the gas from which the parent stars formed.

With the exception of the He/H ratio, direct abundance determinations require the measurement of the electron temperature  $T_e$ , the electron density  $n_e$ , and line intensities in two or more ionization stages. Because the crucial temperature diagnostic line [OIII]  $\lambda 4363$  is 50 to 200 times weaker than [OIII]  $\lambda 5007$ , the measurement of this faint line sets the distance limit for abundance determinations. To date, direct abundance measurements have not been made in galaxies more distant than M31. Indirect PNe abundance determinations based on diagnostic line ratios have been made in NGC 5128 (Walsh et al. 1999).

Jacoby & Ciardullo (1999) measured the chemical abundances in 15 M31 PNe. Their paper, which finds a wide range in [O/H] in M31's old stellar populations, is a model for these difficult observations.

### 4. The Planetary Nebula Luminosity Function

Image intensifier detections of PNe in M31 and its dwarf companions (NGC 147, NGC 185, NGC 205, and M32) with the Lick 3-m telescope (Ford, Jenner, & Epps 1973; Ford & Jenner 1975; Ford, Jacoby, & Jenner 1977; Ford & Jacoby 1978) and subsequent Image Tube Scanner spectrophotometry showed that the brightest nebulae had approximately the same [OIII]  $\lambda 5007$  flux. We reasoned that if we compared similar old stellar populations, the main sequence turn-off masses would be similar. Consequently, there would be a maximum number of ionizing photons that could be produced by a planetary's central star, and a maximum [OIII]  $\lambda 5007$  flux. Using this reasoning, we proposed that planetary nebulae might be used as standard candles (Ford & Jenner, 1978). Although the utility of the planetary nebula luminosity function (PNLF) has been controversial (Sandage & Tammann 1990; Bottinelli 1991; Tammann 1993), a great deal of observational work (e.g. Ciardullo et al. 1989a; Ciardullo et al. 1989b;

Jacoby et al. 1989) showed that the PNLF in the bulges of spiral galaxies and in early type galaxies is an excellent standard candle with little or no dependence on Hubble type. Analytical, theoretical, and numerical models (Jacoby, 1989; Dopita, Jacoby, & Vassiliadis 1992; Mendez 1993) established the theoretical basis for the observational fact that the PNLF is a good standard candle. These studies showed that the PNLF has only a modest dependence on the ages and metallicities of the parent population, and the number of PNe observed. However, the *observed* dependencies appear to be much smaller than those predicted by the models. Jacoby, Walker, and Ciardullo (1990) found that the observed PNLF distance to the LMC is in excellent agreement with the LMC Cepheid distance.

Ciardullo et al. (1989a; C89a) developed the model for the PNLF that has been used so successfully for deriving distances to galaxies that do not have cepheids. Their representation of the PNLF is given in equation 1.

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

$M^*$  in equation 1 cuts off the luminosity function and serves as a “standard candle”. Based on a distance of 770 Kpc to M31, the calibration of the PNLF was given by  $M^* = -4.48$  (C89a). Using Madore & Freedman’s (1991) Cepheid distance to M31, Ciardullo et al. (1998) derived  $M^* = -4.54$ . More recently Ferrarese et al. (2000) derived  $M^* = -4.58$  by comparing PNLF distances with HST Cepheid distances to the same galaxies, or to galaxies in the same group or cluster. They found a very tight linear relationship between the PNLF and Cepheid distances. The PNLF distances to the Virgo and Fornax clusters appear to be systematically smaller than the Cepheid distances. This may be due to intracluster PNe; in a magnitude-limited sample, these will be preferentially on the nearside of the cluster (see Section 6).

The relationship between the apparent monochromatic magnitude  $m_{5007}$  and the observed monochromatic flux  $F_{5007}$  is given by

$$m_{5007} = -2.5 \log F_{5007} - 13.74. \quad (2)$$

The [OIII]  $\lambda 5007$  flux from an  $M^*$  planetary at 10 parsecs is  $1.977 \times 10^{-4}$  ergs  $\text{cm}^{-2} \text{s}^{-1}$ .

## 5. Summary of Surveys for Extragalactic PNe

At the time of writing, approximately 5000 PNe have been identified in more than 40 external galaxies. These observations are summarized in Table 2. The galaxy types were taken from the RSA (Sandage & Tammann 1980, 1987) when available. Galaxy distances in bold type are based on the PNLF. Column 4 gives the number of PNe identified in each galaxy and column 5 gives the references for the identifications. The sixth column list references for those galaxies that have chemical abundance determinations for their PNe. Space did not permit inclusion of the large number of chemical abundance studies of PNe in the LMC and SMC. References for galaxies with PNe radial velocities and dynamical studies are listed in the last column of Table 2.

Table 2. Observations of Extragalactic Planetary Nebulae

Galaxy	Type	Dist (Mpc)	No. of PNe	ID Refs	Chem Abund Refs	Radial Velocity References
Sag Df	ImIV-V	0.025	2	Z96	W97	Z96
Fornax	Irr III-IV		1	D78	D78,W97	D78
SMC	ImIV-V	<b>0.062</b>	62	M95	*	F68
LMC	Irr	<b>0.049</b>	280	L97	*	F68, S72
LMC						F79b,M88
N 147	dE5		5	F77		F77
N 185	dE3p	0.57	5	F73,F77	R95	F77
N 205	S0/E5p	0.76	28	F73,C89b	R95	
N 6822	ImIV-V		7	K82	K82,R95	
M31	SbI-II	0.77	1000	F78, L82	J86,S98,	L82, L83
M31				C89b	J99,R99	N87, H94
M31					H00	E00
M32	E2	< 0.77	30	F73, F75	J79,S98	N86
M32				C89b	R99,H00	
M33	Sc(s)II-III	0.84	138	M01, C01		
M33		<b>0.85</b>	58	K99		
IC 10	dIrr		1	J81		
Leo A	dIrr		2	J81		
Sex A	dIrr		1	J81		
Peg	dI/dSph		1	J81		
WLM	IrrIV-V		2	J81		
N 300	ScII.8	<b>2.4</b>	34	S96		
M81	Sb(r)I-II	<b>3.50</b>	185	J89		
N 2403	Sc(s)III	<b>3.26</b>	40	K99		
N 5128	S0+S pec	<b>3.5</b>	1140	H93b,P02	W99	H93a,H95
N 5128				F02		M96, M99
N 5128						P02
N 5102	S0_1(5)	<b>3.1</b>	26	M94a		
N 4736	SA(r)ab	6.0	67	D00		D00
N 3627	Sb(s)II.2	<b>10.41</b>	73	K99		
N 3377	E6	<b>10.3</b>	54	C89a		
N 3379	E0	<b>9.8</b>	93	C89a		C93, S99
N 3379						S00
N 3384	SB0	<b>10.1</b>	102	C89a		T95
N 3368	Sab(s)II	<b>9.6</b>	74	F96B		
N 1023	SB0_1(5)	<b>9.86</b>	110	C91		
N 891	Sb	<b>9.86</b>	33	C91		
N 5194	Sbc(s)I-II	<b>8.4</b>	64	F96b		
N 5457	Sc(s)I	<b>7.7</b>	65	F96a,F96b		
N 4594	Sa+/Sb-	<b>8.9</b>	294	F96c		
N 4374	E1	<b>15.7</b>	102	J90		
N 4382	S0_1(3) pec	<b>14.4</b>	102	J90		
N 4406	S0_1(3)/E3	<b>15.7</b>	141	J90		A96
N 4472	E1/S0_1(1)	<b>13.9</b>	54	J90		

Table 2. (Continued)

Galaxy	Type	Dist (Mpc)	No. of PNe	ID Refs	Chem Abund Refs	RV Refs
N 4486	E0	<b>13.3</b>	338	J90, C98		
N 4649	S0_1(2)	<b>14.2</b>	32	J90		
N 4478	E2	<i>13.3</i>	7	C98		
IC3443	dE0		1	C98		
N 1316	Sa pec	<b>16.8</b>	105	M94b		A98
N 1399	E1	<b>17.1</b>	72	M94b		S00
N 1404	E2	<b>17.0</b>	47	M94b		

## 6. Intracluster Planetary Nebulae

The discovery of intracluster planetary nebulae (ICPNe) in the Virgo and Fornax clusters is one of the most interesting new developments in the study of extragalactic PNe. ICPNe were first discovered by Arnaboldi et al. (1996; A96) in a survey of the Virgo galaxy NGC 4406. Spectra were taken of PNe candidates (Jacoby et al. 1990; J90) in two fields that were centered  $134''$ E and  $134''$ W of NGC 4406. Sixteen of the PNe candidates in the two fields have radial velocities near N4406's systemic velocity of  $-227 \text{ km s}^{-1}$ . Three of the candidates in the W field have velocities of  $1729 \text{ km s}^{-1}$ ,  $1651 \text{ km s}^{-1}$ , and  $1340 \text{ km s}^{-1}$ , provided the observed emission line is [OIII]  $\lambda 5007$ . At these redshifts, the [OIII]  $\lambda 4959$  emission line falls in J90's on-band filter ( $\lambda_c \sim 4998 \text{ \AA}$ ,  $\text{FWHM} \sim 30 \text{ \AA}$ ), accounting for the detection of the high velocity PNe. Because the nebulae were identified with a filter centered at  $4998 \text{ \AA}$ , the emission lines detected spectroscopically at  $\sim 5033 \text{ \AA}$  *cannot* be  $\text{Ly}\alpha$  from galaxies with redshifts  $z \sim 3.14$ . A96 suggested that these three nebulae are PNe from a Virgo intracluster stellar population.

Subsequent surveys of the Virgo and Fornax clusters have identified 300 emission line sources that may be ICPNe. The surveys are summarized in Table 3. Column 5 lists the survey authors' estimated fraction of the cluster's total stellar mass that is in the intracluster medium. These estimates suggest that 20% to 50% of a cluster's stellar mass may be in the intracluster medium!

Depending on the depth of the survey, 25% or more of the PNe candidates may be starbursting galaxies at  $z \sim 3.1$  with  $\text{Ly}\alpha$  emission redshifted into the [OIII]  $\lambda 5007$  on-band filter (cf Kudritzki et al. 2000; Krelve et al. 1999; Freeman et al. 2000). Provided there is a sufficient signal-to-noise ratio in the spectra, PNe can be distinguished from starbursting galaxies and QSOs at  $z \sim 3.1$  by the presence of [OIII]  $\lambda 4959$  and the absence of a continuum. At spectral resolutions of  $\sim 10 \text{ \AA}$  or higher, the  $\text{Ly}\alpha$  emission line will be resolved, whereas [OIII]  $\lambda 5007$  in a PN with an expansion velocity of  $\sim 20 \text{ km s}^{-1}$  will be unresolved.

Several arguments suggest that a large fraction of the ICPNe candidates are in fact intracluster planetary nebulae. Freeman et al. (2001) spectroscopically confirmed 23 ICPNe in the Virgo cluster by detecting [OIII]  $\lambda 4959$  and [OIII]  $\lambda 5007$  at the expected wavelengths and intensity ratio. The anomalous

Table 3. ICPNe Candidates in the Virgo and Fornax Clusters

Cluster	Fields	Survey Area (sq-arcmin)	Num. of ICPNe <i>Candidates</i>	IC-Stellar Fraction	Refs
Virgo	N 4406	32	3	–	A96
Virgo	Virgo Core	50	11	0.5	M87
Virgo	2 Intracluster	512	85	0.2	F98
Virgo	M87 Halo	256	~ 75	–	C98
Virgo	Intracluster	–	23 confirmed	–	F00
Fornax	Intra-cluster	104	10	0.4	T97
Fornax	Intra-cluster	0.58 sq-deg	~ 135	0.15 - 0.2	K00

PNLF in M87’s halo has PNe that are brighter than the PNe in M87’s main body, and thus are likely foreground ICPNe (Ciardullo et al. 1998). SN 1980I occurred midway between NGC 4374 and NGC 4406, showing that there are intracluster stars in the Virgo cluster (Smith, 1981). Ferguson, Tanvir, & von Hippel (1998) used HST images to detect faint intracluster stars in isolated Virgo fields. This population of (old) stars will produce planetary nebulae.

ICPNe are important for many reasons. They may provide *thousands* of test particles for detailed studies of the mass distribution in clusters. Their kinematics may reveal otherwise unobservable tidal streams that record tidal interactions over the last few Giga-years.

Little is known about the presence of intragroup stars in small groups of galaxies. If groups of galaxies have the same fraction of luminous intergalactic material as estimated for Virgo and Fornax, there could be hundreds of intergalactic PNe. The kinematics of these nebulae could be used to investigate the distribution of mass in sparse groups, and to study the history of tidal interactions.

## 7. Stellar Populations in Cen A’s Halo

PNe and globular clusters (GCs) are both used as probes of galaxy halos. While PNe sample the field star population, and have emission lines that are more conducive to identification and radial velocity measurements, GCs are old star clusters for which we also can obtain metallicity and size information. Together, PNe and GCs are complementary tools for studying the structure and evolutionary histories of early-type galaxies.

At a distance of 3.5 Mpc (Hui et al. 1993; H93b), Centaurus A (NGC 5128) is the nearest massive elliptical galaxy, making it an excellent target for PNe and GC studies. Previous PNe surveys (H93b, Hui et al. 1995; H95) identified 785 PNe out to 20 Kpc along the major axis and 10 Kpc along the minor axis, and resulted in velocities for 433 PNe. We recently completed an extended survey that reaches projected radii of 80 and 40 Kpc along the major and minor axes, respectively. This brings the total number of PNe to 1140, of which 736 have velocities. In addition, we conducted a UBVRI survey with spectroscopic follow-up out to 50 and 30 Kpc to find new GCs and study the faint halo light.

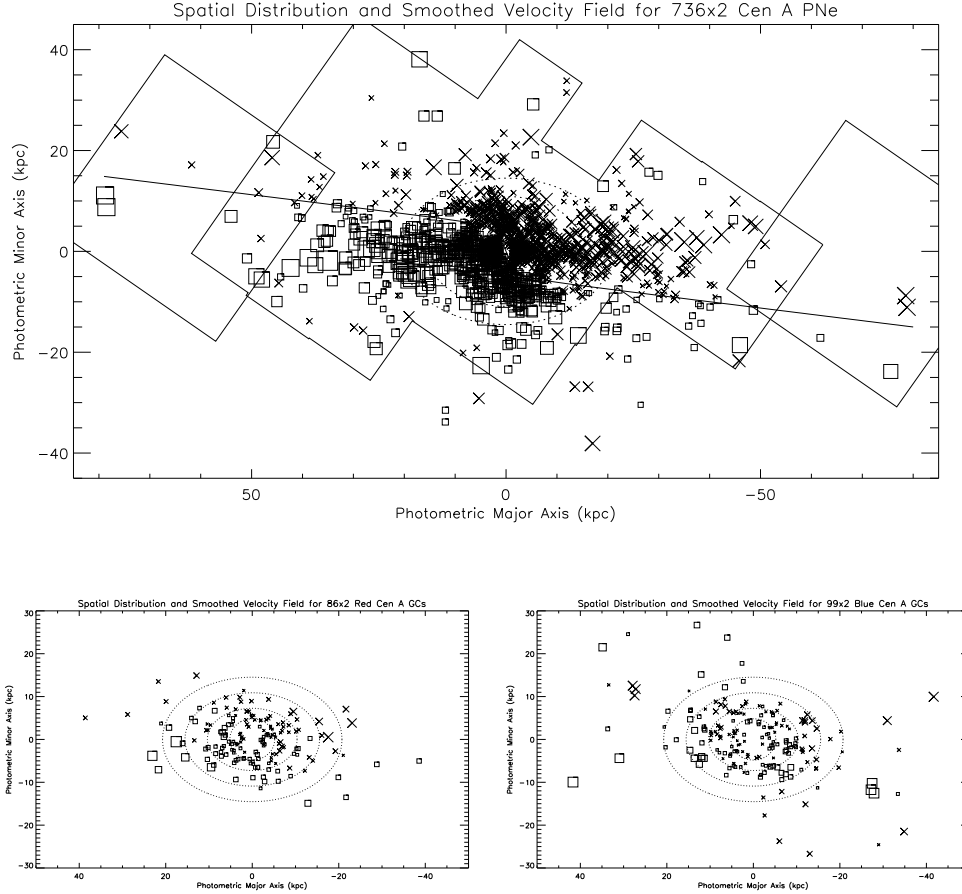


Figure 1. *Cen A PN and GC Smoothed Velocity Fields.* The x/y-axes are the photometric major/minor axes. The dotted ellipses are 1–4  $r_e$  isophotes for the old stellar light. Each point is a confirmed PN or GC. The mean velocity field at each object is the radial velocity average of all objects within  $r \leq 3$  Kpc. In sparse regions, the velocities are averaged with nearby neighbors. Velocities greater/less than systemic are represented by an “x”/box, with a point size proportional to the absolute deviation from systemic (up to  $\sim \pm 150$  km/s). We assume point symmetry (valid in a triaxial potential), and reflect each object through the origin while reversing the sign of its velocity wrt the galaxy. a) (top) *The PN velocity field.* Overplotted are the outlines of our survey (large boxes), and the zero velocity contour. Points appear to exist outside our survey area because of the assumed point symmetry, creating a 1472 particle field. The zero-velocity contour has a strong twist in the inner regions. b) (bottom left) *The Red GC Velocity Field.* There are 86 GCs redder than  $(V-I)_0 = 0.98$ , the dip in the bimodal color distribution. These GCs are more centrally concentrated than the blue GCs, and rotate in a sense similar to the PNe. c) (bottom right) *The Velocity Field for 99 Blue GCs.* These are more extended than the red GCs, and have kinematics less similar to the PNe.



In total, there are now 188 GCs with measured velocities in Cen A, 125 of which are newly discovered from our survey.

The smoothed PN velocity field shown in Figure 1 is the most detailed and extensive stellar velocity field in an elliptical galaxy to date. The rotation in the halo, discovered at 20 Kpc in previous work (H95), is now evident to the 80 Kpc limit of our survey. Most striking, however, is the previously undetected twist in the zero-velocity contour. Earlier work detected kinematic misalignments in Cen A and in other ellipticals (H95; Franx, Illingworth, & Heckman 1989), but this is some of the first compelling evidence for a twist in the kinematic axis. Misalignment and twisting of the kinematic axis are predicted for triaxial galaxies seen in projection (Statler 1991), and also are seen in merger simulations (e.g. Bendo & Barnes 2000). This program is an excellent advertisement for the potential of future PNe surveys.

Globular cluster candidates were identified from UBVRI CCD imaging based on morphological and color criteria. Radial velocities confirm membership in the Cen A GC system ( $V_{systemic} = 541 \text{ km s}^{-1}$ ), and provide kinematic information. We constructed the velocity fields for the GCs using our observations of new and known GCs, combined with 29 velocities from Harris et al. (1992). The  $V-I$  color distribution of GCs is confirmed to be bimodal. Using the  $V-I$  color, a proxy for metallicity in old stellar systems, we can separate the GCs into blue (metal-poor) and red (metal-rich) populations. Figure 1 shows the spatial distribution and velocity fields of the two GC populations. The red GCs are more centrally concentrated, and more rotationally supported than the blue GCs. The kinematics of the PNe are more like those of the red GCs than the blue. This is consistent with the field stars in Cen A being predominantly metal-rich (Harris & Harris 2001), and with the red clusters and PNe having a common formation history.

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