A SURVEY FOR PLANETARY NEBULAE IN M31 GLOBULAR CLUSTERS

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ABSTRACT

We report the results of an [OIII] λ5007 spectroscopic survey for planetary nebulae (PNe) located within the star clusters of M31. By examining R ~ 5000 spectra taken with the WIYN+Hydra spectrograph, we identify 3 PN candidates in a sample of 274 likely globular clusters, 2 candidates in objects which may be globular clusters, and 5 candidates in a set of 85 younger systems. The possible PNe are all faint, between ~2.5 and ~6.8 mag down the PN luminosity function, and, partly as a consequence of our selection criteria, have high excitation, with [OIII] λ5007 to Hβ ratios ranging from 2 to ≥12. We discuss the individual candidates, their likelihood of cluster membership, and the possibility that they were formed via binary interactions within the clusters. Our data are consistent with the suggestion that PN formation within globular clusters correlates with binary encounter frequency, though, due to the small numbers and large uncertainties in the candidate list, this study does not provide sufficient evidence to confirm the hypothesis.

Key words: galaxies: individual (M31) — globular clusters: general — planetary nebulae: general — stars: evolution

Online-only material: color figures, machine-readable table

1. INTRODUCTION

Despite over a century of observations and decades of detailed modeling, the stellar population that forms planetary nebulae (PNe) is still somewhat of a mystery. The traditional theory states that the progenitors of PNe are low- to intermediate-mass single stars at the end of the asymptotic giant branch (AGB) phase (Shklovski 1956; Abell & Goldreich 1966). This hypothesis explains the distribution of PNe throughout space, and is responsible for the widely-held belief that the Sun will eventually evolve through this easily identifiable nebular phase (e.g., Abell & Goldreich 1966; Ciardullo et al. 1989; Buzzoni et al. 2006). However, this theory does not provide a natural explanation for the non-spherical morphologies observed for these and other inconsistencies (see De Marco 2009), a new paradigm has been developed, wherein most PNe are shaped via the interaction of an AGB wind with a binary companion (e.g., Soker 1997).

Unfortunately, while the binary interaction model explains some of the anomalies associated with the observed PN population (Moe & De Marco 2006, 2012; De Marco 2009), this theory awaits final confirmation: the number of PN central stars with known binary companions is still relatively small, and programs to detect such objects are extremely challenging (De Marco et al. 2011, 2013). Moreover, neither the single-star nor binary-star hypothesis can explain the luminosities observed for PNe in the old stellar populations of elliptical galaxies and spiral bulges (Ciardullo et al. 2005), nor the invariance of the bright end of the planetary nebula luminosity function (PNLF) across stellar populations (Ciardullo et al. 2002). For this, one must invoke yet another formation scenario, wherein significant mass transfer (or a complete stellar merger) occurs prior to the PN phase (Ciardullo et al. 2005; Soker 2006).

It is difficult to probe the different PN formation scenarios using field stars, since one has almost no prior information about the properties of the PN progenitors. However, within star clusters, the situation is different, as both the age and metallicity of the progenitor can be accessed. Moreover, the low turnover mass of old globular clusters (GCs) provides a tool with which to probe the binary formation scenario directly. Because GCs generally have turnover masses less than 1 M⊙, any post-AGB core arising from simple single-star stellar evolution must have a very small mass, Mcore ≲ 0.54 M⊙ (Kalirai et al. 2008), and an extremely long evolutionary timescale, t > 105 yr (e.g., Caloi 1989). Such objects cannot make PNe by themselves, since the mass lost during the AGB phase will disperse long before the core becomes hot enough to generate ionizing radiation. Any PN detected in these systems must therefore come from an alternate evolutionary channel, such as a common-envelope interaction or a mass augmentation process (i.e., a stellar merger).

Searches for PNe in Galactic clusters have turned up only a few associated objects. Although more than a dozen PNe are projected near open clusters, the vast majority are undoubtedly line-of-sight coincidences (Majaess et al. 2007; Parker et al. 2011). Similarly, out of 130 Galactic GCs surveyed, only 4 host PNe: Ps 1 in M15 (Pease 1928), GJJC-1 in M22 (Gillett et al. 1986), JaFu1 in Pal 6, and JaFu2 in NGC 6441 (Jacoby et al. 1997). Two of these PNe have high mass central stars more appropriate to PNe within open clusters (~0.62 M⊙ for Ps 1 and ~0.75 M⊙ for GJJC-1; Bianchi et al. 2001; Harrington & Platoglou 1993), while the others have highly non-spherical nebulae (De Marco 2011). The true nature of GJJC-1 is currently being re-assessed due to its high stellar mass, low
Figure 1. The locations of our WIYN+Hydra fields and the targeted M31 clusters, superposed on a mosaic of [O iii] images from Massey et al. (2007). North is up and east is to the left. Each 1° colored circle represents a different Hydra setup.

A color version of this figure is available in the online journal.

nebular mass, and bizarre chemical composition (G. H. Jacoby et al. 2013, in preparation), but for this paper, we adopt the usual PN classification.) These facts, along with the observation that three of the four PNe are located in clusters that are rich in X-ray sources, suggest that interacting binaries play a role in the formation of cluster PNe (Jacoby et al. 1997).

Since the sample of PNe within Galactic GCs is small, the significance of any conclusion based on their properties is low. To better understand the processes that form PNe within clusters, many more objects are required. For this, we must look to other galaxies. Unfortunately, while there have been a few isolated associations of [O iii] emission arising from M31’s disk, several fibers in each setup were offset onto regions of blank sky.

Our specific target selections were made using the fiber-assignment program whydra. Since the M31 GC system covers a much larger area than the 1° field-of-view of the WIYN+Hydra instrument (see Figure 1), we began by visualizing the locations of the individual clusters using the [O iii] images of the Local Group Galaxies Survey (Massey et al. 2007). To accommodate the bulk of the galaxy’s cluster population, we located our first four setups on M31’s bulge. Thereafter, we alternated between regions southwest and northeast of the galactic center, each of which were covered by more clusters. In total, 8 different setups were executed over the 4 nights of the observing run, and data were acquired for 391 RBC clusters, 64 X-ray clusters, and 12 young clusters, with 30 of the systems being targeted more than once. An additional 55 of M31’s field PNe were also observed. A log of the observations is given in Table 1.

Table 1

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<td>M31-R2</td>
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<td>7 × 30</td>
<td>16</td>
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2. OBSERVATIONS AND REDUCTIONS

On 2008 October 25–28 (UT), we targeted 467 candidate star clusters in M31 with the 3.5 m WIYN telescope on Kitt Peak and the Hydra multi-fiber spectrophotograph. The objects selected for study were largely taken from a list of clusters given in the Revised Bologna Catalog (RBC; Galleti et al. 2004, 2007) and supplemented using the X-ray cluster identifications of Fan et al. (2005) and the young cluster candidates of Caldwell et al. (2009). As a control, we also positioned spare fibers on known M31 PNe taken from the list of Merrett et al. (2006).

To execute these observations, the WIYN+Hydra system was configured to use the instrument’s array of 3" diameter blue-sensitive fibers, the WIYN Bench spectrograph, and a 740 lines mm−1 Volume Phase Holographic (VPH) grating designed to optimize throughput near 5000 Å. The resultant spectra covered the wavelength range between 4400 Å and 5450 Å at 1 Å resolution and 0.5 Å pixel−1. Typically, each Hydra setup was observed for 3.5 hr via a series of seven 30 minute exposures.

Our initial reduction procedures were similar to those described in Herrmann & Ciardullo (2009). We began with the...
tasks within the IRAF\textsuperscript{8} package: the data were trimmed and bias-subtracted via ccdproc, dome flats (typically three per setup) were combined using flatcombine, and CuAr comparison arcs, which bracketed the program exposures, were combined via imcombine. Next, dobydra within the hydra package was used to combine and linearize the spectra, with the averaged dome flats serving to define the extraction apertures, and the averaged comparison arcs providing the wavelength calibration. We estimate these wavelength calibrations to be precise to 0.04 Å yielding 1σ errors of ∼2.4 km s\(^{-1}\). As we illustrate below, this is small in comparison with the other uncertainties associated with our radial velocity determinations.

After extracting each spectrum, the program objects were sky subtracted using the data acquired through our blank-field fibers. This step was straightforward: since all the data were taken in dark time and no bright sky lines fell within the wavelength range of the instrument, we simply used combine to combine the extracted spectra from the multiple exposures and then invoked sky subtract to perform the subtraction. As will be explained in Section 3, our searches for PN emission involved the subtraction of template spectra derived from the data themselves. Since these templates underwent the same sky subtraction, our procedure was differential in nature, and the details of sky subtraction had no significant effect on the analysis.

The final step in the basic data reduction involved estimating the response function of our instrument. Relative spectrophotometry across the entire spectral range of WIYN+Hydra was unnecessary for our program. Instead, we concentrated on determining the instrumental sensitivity at H\(\beta\) and [O \textsc{iii}] \(\lambda 4959\) relative to [O \textsc{iii}] \(\lambda 5007\). The [O \textsc{iii}] \(\lambda 4959\) calibration was straightforward. Of the 55 PNe targeted via our spare fibers, all but one were recovered in [O \textsc{iii}] \(\lambda 5007\), and 51 out of 55 had detectable [O \textsc{iii}] \(\lambda 4959\). By comparing the observed ratio of the oxygen doublet to the astrophysical ratio of 2.92, we concluded that the spectroscopic throughput at 4959 Å was ∼90% that at 5007 Å.

The procedure for estimating the instrumental response at H\(\beta\) was slightly more complicated. We began by identifying 15 bright clusters and comparing their continuum flux near 5000 Å to that surrounding the H\(\beta\) line. Spectral libraries (e.g., Jacoby et al. 1984) show that, after applying M31’s foreground reddening \((E(B-V) = 0.062); Schlegel et al. 1998\), the spectral energy distributions of old stellar populations should be flat between 4800 Å and 5100 Å. Consequently, to estimate the relative system response at H\(\beta\), we simply adopted the inverse of the observed \(\lambda 5007\) to H\(\beta\) continuum ratio. Our estimate of 68% is slightly greater than the 62% value expected from the Bench spectrophotograph system and the VPH grating (Bershady et al. 2008). However, since the efficiency of this grating is only known to ∼10%, the two numbers are consistent.

Figure 2 compares the [O \textsc{iii}] \(\lambda 5007\) counts recorded in our PN spectra to the objects’ apparent magnitudes as determined by the counter-dispersed imaging of Merritt et al. (2006). There is a substantial amount of scatter in the diagram due to the photometric and astrometric errors associated with the measurements from the Planetary Nebula Spectrograph, imperfections in our fiber positioning, and the effects of variable sky conditions. Nevertheless, the data demonstrate that our observations go quite deep: since we can detect emission lines containing as few as ∼100 counts, our observations are sensitive to PNe that are ∼6 mag down the luminosity function.

3. FINDING PNe WITHIN STAR CLUSTERS

Three criteria must be met before we can claim the detection of a PN candidate within an M31 star cluster. First, we must identify the presence of emission lines in the spectrum of the cluster. Second, the observed emission lines must have line-ratios consistent with those expected from a PN. Because of our limited spectral coverage (chosen to achieve the resolution needed to optimize emission line detections), this criterion is equivalent to requiring that the ratio of [O \textsc{iii}] \(\lambda 5007\) to H\(\beta\) be greater than some threshold (see below). Third, the velocity of a PN candidate, as derived from its emission-lines, must be consistent with that of a star bound to its parent star cluster. Since the escape velocity from a typical M31 cluster is low, the precision of our emission-line and absorption line velocity measurements is an important parameter for our selection criteria.

3.1. Detection of Emission Lines

To search for PN emission within GCs, we began by normalizing each program spectrum with the continuum command within IRAF. We next divided the spectra into five classes based on the strengths and widths of the absorption features, thereby effectively grouping the clusters by age and metallicity. The highest signal-to-noise spectrum of each class was then chosen as a template, and shifted to zero velocity using, as a reference, the absorption lines of H\(\beta\), the Mg\(b\) triplet (\(\lambda\)5167, 5173, 5184), and other strong features. The remaining clusters of the class were then cross-correlated against their template to determine their relative radial velocities, and shifted to the rest frame. Finally, to improve the detectability of any faint emission feature which may be lost amidst the background light, the template spectra were scaled and subtracted from the other members of their class. Figure 3 shows the five template spectra.

Figure 4 illustrates this template-subtracting procedure using the globular cluster B094-G156. This example is representative
Figure 3. Spectra of the five template clusters used to suppress the stellar continuum and enhance the visibility of emission lines. The strongest absorption in this part of the spectrum comes from H\textsc{β}; most of the others lines are due to iron. The differences between spectra represent variations in cluster’s age and metallicity.

of our reductions; some of the template subtractions are much better, while others are poorer (see Section 4). In particular, because there were only five template clusters, not all the observed systems flattened as well as the one that is displayed. In particular, several of the clusters classified as “young” by Caldwell et al. (2009) had imperfect subtractions around H\textsc{β}. Nevertheless, in virtually all cases, the technique worked well around 5007 Å, as it effectively suppressed the continuum, allowing us to detect extremely weak emission from [O\textsc{iii}]. Moreover, even when H\textsc{β} was poorly subtracted, we could still measure the emission-line ratios extremely well, as the underlying stellar absorption was far broader than the unresolved Balmer emission.

3.2. The Emission-line Signature

Our next step was to look for evidence of PN emission. Because our data were taken using a multi-fiber spectrograph rather than traditional slit spectroscopy, local sky subtraction was not possible. Consequently, the emission arising from the diffuse ionized gas of M31’s disk could not always be removed cleanly, and, even in the galactic bulge, line contamination was frequently a problem (see Ciardullo et al. 1988 for an image of M31’s bulge emission). In fact, as summarized in Table 3, roughly one-third of the GCs surveyed displayed some evidence of emission, mostly due to M31’s warm interstellar medium (ISM).

To guard against this form of false detection, we considered the expected line ratios of a PN. Most bright PNe are high excitation objects: in the top 2.5 mag of the [O\textsc{iii}] PNLF, all PNe have [O\textsc{iii}] \(\lambda5007\) to H\textsc{α} ratios greater than 3 (i.e., \(I(\lambda5007)/I(H\alpha) \gtrsim 9\)), and even at fainter magnitudes, [O\textsc{iii}] \(\lambda5007\) is usually twice the strength of H\textsc{β} (Ciardullo et al. 2002; Herrmann & Ciardullo 2009). In the metal-poor environments of GCs, this lower limit is even more appropriate: of the 11
halo and GC PNe observed by Howard et al. (1997) and Jacoby et al. (1997), all have an excitation parameter, \( R = I(\lambda 5007)/I(\lambda H\beta) > 2 \). In contrast, the vast majority of M31’s \( H\alpha \) regions and diffuse ionized emission have \( H\beta \) brighter than \( [O\, iii] \lambda 5007 \) (e.g., Blair et al. 1982; Galarza et al. 1999; Greenawalt et al. 1997). Moreover, in those rare cases where an \( H\alpha \) region does exhibit a high value of \( R \), its ionizing source (either a single O star or a very young OB association) must be very hot. Such an object will therefore be very luminous—more than 100 or 1000 times the brightness of a PN central star—and detectable either via its blue continuum or its overly bright emission-line luminosity.

The only other sources that may have an excitation similar to that of a PN are supernova remnants (SNRs), supersoft X-ray sources, and symbiotic stars. SNRs are relatively rare (a factor of \(~10 \) less numerous than PNe), and those remnants with \( R > 2 \) are less common still (Magnier et al. 1995; Galarza et al. 1999). If a SNR were embedded within one of our target clusters, it would likely be much brighter and/or have much broader emission lines than any PN. Supersoft X-ray sources are even rarer than SNRs, and most either have sizes much larger than a star cluster (Remillard et al. 1995) or are associated with classical novae (Pietsch et al. 2005). In this latter case, the nova ejecta would have a velocity structure that is easily resolvable in our \( R \sim 5000 \) spectra. Finally, symbiotic stars can produce high-excitation emission lines, and in some cases their observed properties can be very similar to those of true PN (Frankowski & Soker 2009). In fact, Soker (2006) has argued that all the bright PNe seen in extragalactic surveys are actually symbiotic stars. But this is hard to prove, and PN surveys in the Milky Way and the LMC find that symbiotic systems are only a minor contaminant (Vigroux et al. 2009; Miszalski et al. 2011). Thus, emission-line sources that have \([O\, iii] \lambda 5007\) more than twice the strength of \( H\beta \) are much more likely to be PNe than \( H\alpha \) regions, SNRs, or some other line-emitting object.

Another way of testing for unrelated line emission is through the use of direct images. Deep \( H\alpha \) and \([O\, iii] \lambda 5007\) Mosaic CCD frames of a 2.2 deg\(^2\) region along M31’s disk are available through the Local Group survey program of Massey et al. (2007). These images, which reach point-source flux limits of \( \log F \sim −15.7 \) in \( H\alpha \) and \( \log F \sim −15.5 \) in \([O\, iii]\), can be used to examine the immediate environment of each cluster. Although not useful for weak emission, the frames provided a check for objects where the evidence for an associated PN was ambiguous.

3.3. Associating a PN Candidate with a Star Cluster

Even when high-excitation emission was detected in our fibers, its source was not always associated with the underlying GC. Some of the emission within M31’s disk does have relatively high excitation, and there is always the possibility of a chance superposition of a cluster with a true but unassociated PN. We can quantify the latter likelihood by computing the probability that a field PN would be projected within 1′ of an M31 cluster entirely by chance. As in other galaxies, the distribution of M31 PNe closely follows that of the galactic light (Merrett et al. 2006), and, from the surface photometry of Kent (1987) and the bolometric corrections of Buzzoni et al. (2006), we calculate that \( \sim 2 \times 10^5 \, L_\odot \) of M31’s diffuse luminosity (i.e., exclusive of the GCs) is projected within our survey fibers. This number, coupled with M31’s luminosity-specific PN density (Merrett et al. 2006), and the PNLF (Ciardullo et al. 1989) implies the existence of \( \sim 0.4 \) superpositions in the top 2.5 mag of the PNLF, and \( \sim 3 \) unassociated PNe within the limits of our survey. Other high-excitation objects, such as old SNRs or supersoft X-ray sources will then increase this number. Clearly, we cannot ignore the possibility that two rather rare objects can be projected within a single optical fiber.

The best way to reject these chance superpositions is to compare the radial velocity of each cluster’s candidate PN to that of its stars. In general, for a PN to be bound to a cluster, the difference, \( \Delta v \), between its emission-line radial velocity and the absorption-line radial velocity of the cluster’s stars should satisfy the criterion \( \Delta v \leq 3 \sigma_{\text{eff}} \), where \( \sigma_{\text{eff}} \) is the quadrature sum of the system’s internal velocity dispersion and the uncertainty in the radial velocity measurements. The former quantity exists for \( \sim 60\% \) of the GCs in our survey, mostly through the \( R \sim 34,000 \) MMT echelle spectroscopy of Strader et al. (2011). For the remaining old stellar systems, we can estimate the line-of-sight velocity dispersions through the clusters’ fundamental plane relation (e.g., Djorgovski et al. 1997; Strader et al. 2009, 2011). While we generally do not have access to information about a cluster’s size or surface brightness, a projection of the Strader et al. (2011) clusters onto the \( M - \sigma \) plane yields

\[
\sigma (\text{km s}^{-1}) \sim 23.5 + 8 M_{T_1} + 0.7 M_{T_1}^2 \]

where \( M_{T_1} \) is the cluster’s absolute \( T_1 \) magnitude in the Washington system (Kim et al. 2007), and \( \sigma \) is the observed velocity dispersion. Typically, these velocity dispersions span the range \( 3 \text{ km s}^{-1} \leq \sigma_0 \leq 30 \text{ km s}^{-1} \), with a median value near \( \sim 8 \text{ km s}^{-1} \). Young clusters do not necessarily follow this relation, but from the structural analysis by Barmby et al. (2009), their line-of-sight velocity dispersion should be small, \( \sigma_0 \lesssim 3 \text{ km s}^{-1} \).

The second term which enters into \( \sigma_{\text{eff}} \) is that arising from the uncertainty of our velocity measurements. This error has two components. The first, which is associated with our centroiding of the \([O\, iii] \lambda 5007\) emission line, is generally small: our velocity measurements typically have errors that are less than \( \sim 5 \text{ km s}^{-1} \). This is in agreement with the results of Herrmann & Ciardullo (2009), who used the same telescope and instrument setup to obtain \( \lesssim 5 \text{ km s}^{-1} \) precision for faint PNe in distant galaxies.

The other component of the error term, that coming from the absorption line measurements, is more complex. Almost half of our clusters have high-quality \( (\sigma_v \lesssim 3 \text{ km s}^{-1}) \) velocity measurements, mostly through the MMT + Hectochelle observations of Strader et al. (2011). As the left panel of Figure 5 shows, there is no systematic difference between our measurements and those of the Hectochelle. Six clusters have highly discrepant velocities, as they differ from their Strader et al. (2011) values by more than three times the internal errors of the measurements. Yet when these objects are removed, the remaining 199 objects have a mean W1YN+Hydra velocity that is just \( \Delta V = 0.2 \text{ km s}^{-1} \) greater than that of the Hectochelle. Since the two sets of observations are on the same system, we can adopt the higher precision Strader et al. (2011) velocities in our analysis.

For most of the remaining clusters, we can use our own velocity measurements, along with their associated measurement errors. As the right panel of Figure 5 illustrates, the dispersion between our independent velocity estimates of clusters observed in more than one Hydra setup is consistent with the expectations of internal measurement error. Moreover, it is possible to obtain a quantitative estimate of our uncertainties by comparing our velocity measurements (and their errors) to those of the Strader
et al. (2011) Hectoechelle data using the $\chi^2$ statistic

\[
\chi^2 = \sum_i \frac{(v - v_S)^2}{(\sigma^2 + \sigma_S^2)}
\]

where $v$, $\sigma$, $v_S$, and $\sigma_S$ represent our velocities and their uncertainties, and those of Strader, respectively. When the 6 discrepant systems are removed, the reduced $\chi^2$ for the 199 degrees of freedom is 0.96. This strongly suggests that the internal errors of our velocity determinations are accurate, and can be adopted as the true uncertainties of our measurements.

Finally, as Figure 5 shows, the typical error of our absorption line velocities is between 15 and 20 km s$^{-1}$. However, a small number of objects have velocity uncertainties that are significantly greater than this. In a few cases, more accurate velocities are available from the literature, and in those cases, we either adopted the previously measured values, or averaged our velocities with the published data. The remaining objects, where our velocity uncertainties were greater than 30 km s$^{-1}$, were excluded from the analysis. Those clusters for which our velocities disagree with previously measured values by more than four times the internal errors are given in Table 2.

4. THE CLUSTERS HOSTING EMISSION

After forming $\sigma_{\text{eff}}$, we excluded all PN candidates with [O iii] $\lambda5007$ velocities that differed from that of their parent cluster by more than 3 $\sigma_{\text{eff}}$. We note that this criterion may not remove all the false detections, since young clusters are expected to have kinematics similar to that of the underlying disk. However, for the older systems, this should be a very effective discriminant. Since the rotation-corrected velocity dispersion of M31’s GC system is $\sim130$ km s$^{-1}$ (Lee et al. 2008), the chance of finding a superposed disk source with the same velocity as one of our candidate clusters is extremely low.

Table 3 lists all the cluster candidates surveyed in this program, along with their published system photometry obtained with the KPNO 0.9 m telescope (Kim et al. 2007), their radial velocities, the equivalent widths of their [O III] $\lambda5007$ emission line, their [O III] $\lambda5007$ to H$\beta$ emission-line ratio, and an age/type classification. For most of the clusters, this classification comes from the analyses of either Caldwell et al. (2009, 2011) or Peacock et al. (2010), and are based on a variety of measurements, including multi-bandpass photometry, Hubble Space Telescope (HST) color–magnitude diagrams, and, in many cases, high signal-to-noise spectra.

Figure 5. Two estimates of the precision of our globular cluster velocities. The left panel compares our data to those of the high-precision measurements of Strader et al. (2011). The solid red points denote objects that differ from zero by more than three times the internal precision of the measurements; three additional systems have velocity discrepancies that fall well off the plot. The right panel shows the velocity differences for clusters observed in more than one Hydra setup. The scatter in these data is 7.6 km s$^{-1}$. The solid points display old (globular) clusters; open circles show younger systems.

Table 2

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<th>Published $v$ (km s$^{-1}$)</th>
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<tr>
<td>SK045A</td>
<td>15.50</td>
<td>+46 ± 7</td>
<td>-544 ± 52</td>
<td>4</td>
<td>11.2</td>
</tr>
<tr>
<td>SK064A</td>
<td>19.30</td>
<td>-35 ± 16</td>
<td>-259 ± 42</td>
<td>4</td>
<td>4.9</td>
</tr>
<tr>
<td>SK079A</td>
<td>18.02</td>
<td>-75 ± 22</td>
<td>-258 ± 26</td>
<td>4</td>
<td>5.3</td>
</tr>
<tr>
<td>SK094A</td>
<td>18.16</td>
<td>-158 ± 21</td>
<td>-8 ± 29</td>
<td>4</td>
<td>4.2</td>
</tr>
<tr>
<td>SK096A</td>
<td>17.94</td>
<td>-55 ± 9</td>
<td>-313 ± 32</td>
<td>4</td>
<td>4.9</td>
</tr>
<tr>
<td>SK104A</td>
<td>17.37</td>
<td>-171 ± 10</td>
<td>-301 ± 17</td>
<td>4</td>
<td>6.6</td>
</tr>
<tr>
<td>SK106A</td>
<td>18.94</td>
<td>-158 ± 31</td>
<td>-890 ± 38</td>
<td>4</td>
<td>14.9</td>
</tr>
</tbody>
</table>

Notes. $^a$ References: (1) Galleti et al. 2006; (2) Strader et al. 2011; (3) Perrett et al. 2002; (4) Kim et al. 2007.
Figure 6. Washington system photometry of M31 clusters classified by Caldwell et al. (2009, 2011), with blue representing clusters with ages $t \lesssim 2$ Gyr, and red designating globular clusters, $t \sim 14$ Gyr. On the left is a two-color diagram; on the right is a histogram of $C - T_i$ colors. In the absence of a spectroscopic or HST imaging age designation, we classify systems with $C - T_i < 1.2$ as young, and $C - T_i > 1.2$ as old.

(A color version of this figure is available in the online journal.)

<table>
<thead>
<tr>
<th>Name</th>
<th>$T_i$</th>
<th>$\sigma_{T_i}$</th>
<th>$C^a$</th>
<th>$\sigma_C$</th>
<th>$M^a$</th>
<th>$\sigma_M$</th>
<th>Velocity (km s$^{-1}$)</th>
<th>$\sigma_V$ (km s$^{-1}$)</th>
<th>Type $^b$</th>
<th>Ref $^b$</th>
<th>$R^a$</th>
<th>EW ($\AA$)</th>
<th>Notes</th>
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<td>AU010</td>
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<td>0.017</td>
<td>18.325</td>
<td>0.031</td>
<td>17.388</td>
<td>0.019</td>
<td>$-311.7$</td>
<td>20.1</td>
<td>Old</td>
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<td>2.8</td>
<td>0.8</td>
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</tr>
<tr>
<td>B001-G039</td>
<td>16.395</td>
<td>0.005</td>
<td>18.580</td>
<td>0.013</td>
<td>17.377</td>
<td>0.007</td>
<td>$-202.7$</td>
<td>10.9</td>
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<td>3</td>
<td>…</td>
<td>…</td>
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<td>B003-G045</td>
<td>17.151</td>
<td>0.012</td>
<td>18.564</td>
<td>0.014</td>
<td>17.885</td>
<td>0.010</td>
<td>$-376.7$</td>
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<td>…</td>
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<td>B004-G050</td>
<td>16.452</td>
<td>0.007</td>
<td>18.172</td>
<td>0.010</td>
<td>17.255</td>
<td>0.006</td>
<td>$-378.1$</td>
<td>5.9</td>
<td>Old</td>
<td>3</td>
<td>…</td>
<td>…</td>
<td></td>
</tr>
<tr>
<td>B005-G052</td>
<td>15.045</td>
<td>0.002</td>
<td>16.901</td>
<td>0.004</td>
<td>15.905</td>
<td>0.002</td>
<td>$-271.6$</td>
<td>14.1</td>
<td>Old</td>
<td>1</td>
<td>…</td>
<td>…</td>
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</tr>
<tr>
<td>B006-G058</td>
<td>14.967</td>
<td>0.002</td>
<td>16.780</td>
<td>0.003</td>
<td>15.831</td>
<td>0.002</td>
<td>$-232.9$</td>
<td>6.1</td>
<td>Old</td>
<td>1</td>
<td>…</td>
<td>…</td>
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<td>B006D-D036</td>
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<td>18.013</td>
<td>0.013</td>
<td>$-538.1$</td>
<td>28.1</td>
<td>Young</td>
<td>3</td>
<td>…</td>
<td>…</td>
<td>Mean; $\Delta V = 11.6$ km s$^{-1}$</td>
</tr>
<tr>
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<td>16.270</td>
<td>0.006</td>
<td>18.077</td>
<td>0.009</td>
<td>17.103</td>
<td>0.005</td>
<td>$-324.6$</td>
<td>3.6</td>
<td>Old</td>
<td>1</td>
<td>…</td>
<td>…</td>
<td>Mean; $\Delta V = 0.0$ km s$^{-1}$</td>
</tr>
</tbody>
</table>

Notes.

$^a$ Numbers in parenthesis have been transformed into the Washington system using literature $BVI$ measurements and the relations of Bessell (2001).

$^b$ The cluster age/type classification has been adopted from the following references: (1) Strader et al. (2011); (2) Caldwell et al. (2011); (3) Caldwell et al. (2009); (4) Peacock et al. (2010).

$^c$ Derived ratio of [O III] to H$\beta$ using the procedures described in Section 2.

$^d$ Classified on the basis of an emission line a 5046 Å.

$^e$ Classified on the basis of a 50 Å FWHM logarithmic-profile emission line at 4836 Å.

$^f$ Classified on the basis of weak emission at 4548 Å.

$^g$ Both [O iii] $\lambda$5007 and H$\beta$ are well resolved and have the same double-peaked emission profile.

$^h$ Classified using the redshifted emission lines of H$\beta$ and the [O iii] doublet.

$^i$ Classified as a galaxy in the literature, but our spectrum is consistent with the object being a star cluster.

(This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)

Table 3

Globular Cluster Observations

The first three objects give the candidates associated with stellar systems confirmed as being old; the next five list tabulated. The first three objects give the candidates associated with stellar systems confirmed as being old; the next five list tabulated. The first three objects give the candidates associated with stellar systems confirmed as being old; the next five list candidates in the younger clusters. Finally, two of our PN candidates are associated with controversial objects, i.e., cluster candidates which may, in fact, be foreground stars.

To estimate the [O III] $\lambda$5007 magnitudes of the PNe, we used our knowledge of the 5000 Å continuum brightness of candidates in the younger clusters. Finally, two of our PN with stellar systems confirmed as being old; the next five list tabulated. The first three objects give the candidates associated with stellar systems confirmed as being old; the next five list candidates in the younger clusters. Finally, two of our PN candidates are associated with controversial objects, i.e., cluster candidates which may, in fact, be foreground stars.

To estimate the [O III] $\lambda$5007 magnitudes of the PNe, we used our knowledge of the 5000 Å continuum brightness of each cluster, as determined by its Washington system $M$ magnitude (central wavelength 5075 Å). By measuring the strength of [O III] $\lambda$5007 relative to this continuum, i.e., the line’s equivalent width, we could approximate the PN candidate’s 5007 Å monochromatic flux. This flux was then converted to a magnitude via

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

and placed on an absolute scale by assuming a distance of 750 kpc (Freedman et al. 2001) and a differential extinction of $E(B - V) = 0.062$ (Schlegel et al. 1998). On this scale, the brightest PNe in M31 attain a luminosity corresponding to $M_{5007} = -4.5$ (Ciardullo et al. 1989; Merrett et al. 2006). This value is fairly resilient against alternative distant estimates to M31 (e.g., 780 kpc; McConnachie et al. 2005).

Of course, estimating brightnesses in this way carries a substantial amount of uncertainty. While the vast majority of M31 GCs have half-light radii smaller than the 1.5 radius of our fibers, the tidal radii for these objects extend much farther (Barmby et al. 2007). As a result, the light coming through the fiber may not accurately reflect the total magnitude of the cluster, and astrometric errors in the cluster coordinates and fiber positioning only exacerbate the problem.

Moreover, the position of the emission-line source within the GC is unknown. Even if the fiber is centered on the GC, a point-source PN may be offset by more than an arcsec. For example, if the four PNe within the Milky Way clusters were placed at the distance of M31, their typical separation from their cluster’s center would be 0′.3–0′.4, but JaFu 1 in Pal 6 would be offset by a full 1′.8. This means that for three out of the four objects, the photometric error due to their position of the PN within the cluster would be negligible (<1% loss through our 3′ fibers), but in 1′ seeing, JaFu 1’s luminosity would be underestimated by a factor of ~5. In the absence of high resolution imaging,
our spectroscopic [O iii] luminosities are the best that can be achieved for these objects, and likely represent lower limits to the true [O iii] λ5007 brightnesses. Other properties which scale with luminosity, such as the inferred minimum central star mass, would be lower limits as well.

The spectra of our candidate PN-GC associations are shown in Figures 7 and 8. Below we detail their properties.

### 4.1. Globular Clusters

Jacoby et al. (1997) argued that the single stars of old GCs cannot form PNe due to the timescale of their post-AGB evolution: by the time their cores becomes hot enough for ionization, their ejected gas would have dispersed far into the ISM. Thus, Jacoby et al. (1997) concluded that PN formation inside GCs must involve binary stars, either through mass transfer, which increases the core mass to that of a higher mass progenitor, or through a binary interaction, which accelerates the speed of post-AGB evolution (Moe & De Marco 2012). More recently, Buell (2012) has suggested an alternative, wherein the single stars of GCs evolve high mass cores by being enriched in the helium produced by previous generations of star formation in the cluster. In any scenario, however, central star mass is a critical parameter of the PN system, but one that is very difficult to determine, even for Galactic PNe.

We can, however, place limits on the mass of a PN central star using models of post-AGB evolution. At best, the [O iii] λ5007 emission of a PN represents ~10% of the luminosity being emitted from its central star (Dopita et al. 1992; Schönberner et al. 2010). Moreover, for any central star luminosity, there is a minimum core required to generate that energy (Vassiliadis & Wood 1994; Blöcker 1995). If we find that this minimum mass is too high to be produced by the evolution of a single star of an old stellar population, then we will have strong evidence for a previous binary interaction. We apply this approach to our candidate objects.

**Table 4**

<table>
<thead>
<tr>
<th>Cluster</th>
<th>Agea (Gyr)</th>
<th>$M_V$</th>
<th>S/N (5007 Å)</th>
<th>S/N (Hβ)</th>
<th>R6</th>
<th>EW (Å)</th>
<th>$M_{5007}$</th>
<th>$Δv$ (km s$^{-1}$)</th>
<th>$Δv/γ_{eff}$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Globular Clusters</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B115-G177</td>
<td>14</td>
<td>−8.54</td>
<td>72</td>
<td>16</td>
<td>3.0</td>
<td>2.5</td>
<td>−2.0</td>
<td>−5</td>
<td>0.42</td>
</tr>
<tr>
<td>BH16</td>
<td>Old</td>
<td>−6.46</td>
<td>8.3</td>
<td>2.4</td>
<td>4.0</td>
<td>0.7</td>
<td>+0.7</td>
<td>−19</td>
<td>2.71</td>
</tr>
<tr>
<td>NB89</td>
<td>10.4</td>
<td>−6.60</td>
<td>36</td>
<td>12</td>
<td>2.1</td>
<td>1.5</td>
<td>+0.5</td>
<td>−34</td>
<td>1.10</td>
</tr>
</tbody>
</table>

**Young Clusters**

| B458-D049     | 0.5        | −6.73 | 6.0          | 1.6      | 2.1| 0.8    | +0.9       | +18             | 2.87         |
| M040          | Young      | −4.98 | 5.5          | 1.1      | 4.1| 1.6    | +1.5       | +24             | 0.91         |
| C009-LGS04131 | 0.3        | −5.58 | 6.3          | ...      | >6.0| 1.0    | +1.8       | +10             | 0.32         |
| SK018A        | 0.8        | −5.09 | 7.0          | ...      | >4.0| 1.2    | +1.9       | +8              | 0.50         |
| DAO47         | 0.5        | −5.52 | 3.8          | ...      | 3.5| 0.5    | +2.3       | +9              | 0.79         |

**Possible Clusters**

| SK044A        | “Star”     | −5.36 | 15           | ...      | >12| 1.9    | +1.5       | +59             | 0.12         |
| SK051A        | “Star”     | −4.40 | 6.5          | ...      | >5.0| 1.5    | +2.3       | −33             | 1.45         |

**Milky Way Clusters**

| Pal 6/JaFu1   | Old        | −6.79 | ...          | 6.3      | ...| −3.3   | −25        | 0.29           |
| M15/Ps 1     | Old        | −9.19 | 2.0          | ...      | >0.7| +0.7   | +23        | 1.35           |
| NGC 6441/JaFu2| Old        | −9.63 | 3.3          | ...      | >2.8| −21    | −1.06      |               |
| M22/GJIC-1   | Old        | −8.50 | ...          | >50      | ...| +5.1   | −16        | −1.14          |

Notes:

a Age estimate of Caldwell et al. (2009, 2011); Objects labeled as “Star” were classified by Peacock et al. (2010).

b Ratio of [O III] to Hβ.

c Age from Beasley et al. (2005); emission may be warm ISM.

*B115-G177.* According to Caldwell et al. (2011), this GC is old and metal-rich, with [Fe/H] $\sim +0.1 \pm 0.1$. Yet the system harbors an emission-line source that is bright enough to stand out in an Fe5015 versus Fe5270 plot, and hot enough to have an [O iii] λ5007 line that is three times the strength of Hβ. To place a lower limit on the luminosity of the exciting source, we can use the fact that no more than ~10% of a central star’s total luminosity is reprocessed into [O iii] λ5007 (Dopita et al. 1992; Schönberner et al. 2010). Consequently, for a source to be as bright as $M_{5007} \sim −2.2$, its exciting star must be at least ~700 $L_\odot$ and have a mass of at least ~0.54 $M_\odot$. Although low-mass cores are capable of generating this amount of luminosity, their evolutionary timescale is too slow to produce a PN. This is our best candidate for a PN inside an M31 GC and an object formed by binary evolution. It may be coincidental that a rare PN is found in a relatively rare metal-rich, yet old, GC (Woodley et al. 2010), or perhaps the combination of properties is a clue to PN formation.

**BH16.** This cluster, classified as old by Strader et al. (2011), possesses the X-ray source J004246.0+411736 (Fan et al. 2005). Our velocity measurement for the system is relatively poor ($−248 ± 28$ km s$^{-1}$), due to possible contamination from the underlying galactic bulge, and inconsistent with the $−99.9 ± 1.1$ km s$^{-1}$ Hectochelle measurement obtained by Strader et al. (2011). If we adopt the latter value, then the velocity of the superposed [O iii] λ5007 emission line differs from that of the cluster by less than 20 km s$^{-1}$ ($−2.7\sigma_{eff}$), making an association likely. The emission-line source itself has a high-excitation ($R \sim 4$), but is also relatively faint, implying a central star luminosity that may be as low as 100 $L_\odot$.

**NB89.** The Lick indices (González 1993) of this system imply an age of ~10 Gyr and a metallicity of [Z/H] $\sim −0.6$ (Barmby et al. 2000; Beasley et al. 2005), so the object is most likely a GC. Its PN candidate is well-measured, but faint, with an estimated [O iii] λ5007 absolute magnitude that is ~4 mag down the luminosity function. The cluster also barely satisfies...
our selection criteria: [O iii] $\lambda$5007 is just 2.1 times the strength of H\(\beta\), and its inclusion in our list is partly due to the large (\(\sim 30\) km s\(^{-1}\)) uncertainty in our estimate of cluster velocity. If, instead of using our own measurement, we adopt the velocity of $-332 \pm 6$ km s\(^{-1}\) observed by Barmby et al. (2000), then the emission-line’s velocity of $-384 \pm 5$ km s\(^{-1}\) is no longer consistent with it being part of the cluster. N. Caldwell (2012, private communication) reports that forbidden emission from [O ii] and [S ii] are strong, further suggesting that the emission-lines are interstellar in nature.

4.2. Candidate Globular Clusters

SK044A. Caldwell et al. (2009) classify this object as an M31 cluster (of indeterminate age) based on its spectrum and its profile on archival HST frames. In contrast, Peacock et al. (2010) call the object a star, citing their analysis of UKIRT and Sloan Digital Sky Survey (SDSS) data. We also have difficulty classifying the object: although the cluster’s neutral color places it 0.062 \(\pm\) 0.056 mag blueward of our “young” versus “old” dividing line, its measured radial velocity differs from that of M31’s underlying disk by $\sim 100$ km s\(^{-1}\) (Chemin et al. 2009). Further complicating the interpretation is our relatively poor determination for the cluster velocity ($-518 \pm 39$ km s\(^{-1}\)); even when combined with the $-491 \pm 46$ km s\(^{-1}\) measurement of Kim et al. (2007), the resultant $\pm 29$ km s\(^{-1}\) uncertainty still dominates the error budget. Nevertheless, the system is interesting, since its emission line velocity is inconsistent with a warm disk origin, and, with an [O iii] $\lambda$5007 to H\(\beta\) ratio of $\geq 12$, it has the highest emission-line excitation in our sample. The [O iii] $\lambda$5007 line is faint, so that if the emission is powered by a PN, its central star could be fainter than $\sim 150 L_\odot$. Unfortunately, without better velocity information, we cannot say for certain whether the observed 48 km s\(^{-1}\) difference between the cluster’s emission lines and absorption features is indicative of an association or a chance superposition. N. Caldwell (2012, private communication) notes that [S ii] is weak in his spectrum, providing further support for the idea that the emission line is produced in a PN rather than the warm ISM.

SK051A. This is our faintest PN candidate, and another object for which we have a relatively large (22 km s\(^{-1}\)) measurement error. Nevertheless, our derived cluster velocity is in excellent agreement with that found by Kim et al. (2007), and the source does possess high-excitation ($R > 5$) [O iii] emission at a velocity consistent with both estimates. The system has the colors of an old cluster, but without better data we cannot confirm its association with the emission line. Peacock et al. (2010) classify the object as a foreground star based on its appearance on images from UKIRT and SDSS, and N. Caldwell (2012, private communication) notes that the object is not resolved on HST frames. Thus, it is possible that the observed continuum is from a point source contaminant, rather than a compact cluster.

4.3. Young Clusters

B458-D049. The cluster just barely satisfies our criterion, as the velocity of the [O iii] $\lambda$5007 emission-line differs from that of the cluster by 18 km s\(^{-1}\), or $2.9 \sigma_{\text{eff}}$. It is a young system, as
Figure 8. The spectra of five M31 young clusters in the wavelength range between 4800 Å and 5100 Å. To enhance the visibility of the emission lines, the spectrum of a template young cluster been subtracted from each object; in some cases, a mismatch in age has resulted in a poor subtraction around Hβ. The y-axis represents counts; to convert to relative flux, note that the response at Hβ is roughly 1.46 times less than that at [O III] λ5007. For each candidate, the [O III] line is at least twice the strength of Hβ.

evidenced by the poor results of our template subtraction about the Hβ absorption line, and Caldwell et al. (2009) estimate its age at 0.5 Gyr. If the [O III] emission does come from a planetary, then the physics of single-star stellar evolution implies that the PN is a high core-mass object. Specifically, the relationship between age and turnoff mass (Iben & Laughlin 1989), coupled with the initial-mass–final-mass relation (Kalirai et al. 2008) yields $M_{\text{core}} \sim 0.66 M_\odot$. If the emission does come from a cluster PN, then the object either evolved from a single massive (young) star and is now well-past its peak [O III] λ5007 brightness of ~8000 $L_\odot$, or it was created through a binary pathway and is likely the result of common envelope evolution. One can sometimes distinguish between these two possibilities in the Galaxy where morphology and abundance anomalies provide some discrimination (Miszalski et al. 2013). At the distance of M31, luminosity is the primary indicator; if an object is very bright, then it likely derives from a single massive star.

M040. Caldwell et al. (2011) re-classified this object as young, though they did not estimate an age. [O III] λ5007 is well-measured, [O III] λ4959 is weak, and Hβ is virtually undetectable. The velocity agreement between the set of emission lines and that of the underlying cluster continuum is not particularly good, between 13 and 28 km s$^{-1}$, depending on whether we adopt our velocity or that of Caldwell et al. (2011). Given the ~30 km s$^{-1}$ uncertainties of both measurements, an association remains a possibility.

C009-LGS04131. Our velocity for this faint system is poor ($-483 \pm 51$ km s$^{-1}$) but it is in excellent agreement with the value of $-495 \pm 32$ km s$^{-1}$ measured by Caldwell et al. (2009) and with the velocity of its [O III] λ5007 emission line ($-484 \pm 5$ km s$^{-1}$). The cluster itself is young, with an age of ~0.3 Gyr (Caldwell et al. 2009) and a turnoff mass of ~3.1 $M_\odot$ (Iben & Laughlin 1989). Although [O III] λ5007 is rather faint, ($M_{5007} \sim +1.7$), it is well-measured, and whatever is causing the emission has a very high excitation, $R > 6$. If the exciting source is a planetary, then, based on the turnoff mass, it is either a ~0.73 $M_\odot$ core mass object which has faded substantially since its peak luminosity, or an object that was formed through a binary interaction.

SK018A. We observed this young cluster twice, with consistent results ($\Delta v = 6.5$ km s$^{-1}$). Caldwell et al. (2009) estimate the age of the cluster to be ~0.8 Gyr, which implies a turnoff mass of ~2.1 $M_\odot$ (Iben & Laughlin 1989) and a PN core mass of ~0.62 $M_\odot$ (Kalirai et al. 2008). Like C009-LGS04131, the object is more than ~6 mag down the [O III] λ5007 PNLF. There is no evidence of Hβ, which implies $R > 4$.

DAO47. Our velocity, when combined with two other determinations in the literature (Perrett et al. 2002; Caldwell et al. 2009), yields a value that is within 9 km s$^{-1}$ of that measured for the [O III] line. The spectrum is relatively noisy, and even after template-subtraction, residual stellar Hβ absorption is still visible. Nevertheless, [O III] λ5007 is reasonably well-detected, and the narrow Hβ emission line is completely absent. Caldwell et al.
estimate the age of the system to be $\sim 0.5$ Gyr, which, in terms of turnoff mass, is $\sim 2.5 M_\odot$ (Iben & Laughlin 1989). The initial mass-final mass relation then implies $M_{\text{core}} \sim 0.66 M_\odot$.

5. DISCUSSION

5.1. Expected and Observed Numbers of PN Candidates

In their survey of 130 Milky Way GCs, Jacoby et al. (1997) identified 4 PNe. Since our M31 survey targeted $\sim 270$ old clusters, a simple scaling of numbers suggests that we should have found $\sim 8$ PNe in our survey. However, only two of the Milky Way objects (Ps 1 in M15 and JaFu 1 in Pal 6) would have been definitively detected by our observations. At the distance of M31, JaFu 2, which is $7.3$ mag down the PNLF, would be at, or just below, the threshold for detection, and GJJC-1 in M22 (which may not be a true PN) would be well past our detection limit. Consequently, we might expect to see $\sim 4$ objects; our list of systems with PN candidates contains three confirmed GCs, and two other sources which may be old systems.

It is unlikely that all of these candidates are true PNe, but the data are marginally consistent with the results of the Galactic surveys. Of the five candidates, one appears to be an excellent PN identification associated with an old cluster. If the other four candidates are ultimately rejected, then the number of PNe in M31 GCs found in this study is four times lower than expected. This can be explained, in part, as a consequence of the observational challenges of the project.

Similarly, our data are consistent with the results of the Peacock et al. (2012) survey of the Virgo giant elliptical NGC 4472. Their observations of 174 luminous GCs covered $\sim 2 \times 10^8 L_\odot$ of bolometric light, and extended $\sim 2.5$ mag down the PN luminosity function. Our observations surveyed $\sim 2.5$ times less light, but extended $\sim 3.5$ mag further down the PN luminosity function. If we assume that the PNLF of GCs is similar to that of the field stars of old populations, i.e.,

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

then the NGC 4472 observations imply that we should have seen $\lesssim 2$ PN in our survey. This, again, is consistent with our data.

Conversely, the number of PN candidates found in young clusters is far more than anticipated. The total luminosity of all the young clusters included in our survey list is rather small, $M_V \sim -9.6$, and only $M_V \sim -8.6$ was surveyed with good velocity precision. Because the young clusters are members of the disk population, their velocities are far more likely to match the velocities of potential interlopers (e.g., H ii regions, SNRs, disk emission) that are also in the disk, than would the old clusters. We therefore must exercise additional caution when evaluating these candidate PNe.

If we assume a bolometric correction of $-0.85$ (Buzzoni et al. 2006), this implies that our survey of young clusters sampled $5 \times 10^9 L_\odot$ of light. From the theory of stellar energy generation, the bolometric luminosity stellar evolutionary flux for systems with ages between $\sim 0.1$ and $\sim 1$ Gyr is $\sim 1 \times 10^{-11}$ stars yr$^{-1}$ L$^{-1}$ (Renzini & Buzzoni 1986). Thus, we might expect these populations to produce one PN every $\sim 200,000$ years. Even if these PNe remained visible for 50,000 yr, that is still not enough time to build up a detectable population. It is therefore likely that the larger velocity errors associated with these fainter clusters, and the kinematic similarity of the clusters and the field exacerbate our ability to discriminate PN candidates from superposed disk emission.

5.2. Are Binary Stars Important

Ciardullo et al. (2005) have argued that blue stragglers are responsible for most, if not all, of the bright PNe found in elliptical galaxies. Not only do these objects possess the main-sequence masses needed to build high-mass post-AGB cores, but their evolutionary timescale, relative to that of PN ($\sim 10^6$), is roughly the same as the relative numbers of the two objects. Since the creation of blue stragglers in GCs may, in some way, be related to the rate of stellar encounters, $\Gamma$ (i.e., Davies et al. 2004; Leigh et al. 2011), then it is at least possible that the probability of finding a PN would also be proportional to this factor. From Verbunt & Hut (1987), this means that

$$N(\text{PN}) \propto \Gamma \propto \frac{\rho_0^2 r_i^3}{\sigma}$$

where $\rho_0$ is the cluster’s central luminosity density, $r_i$ is the core radius, and $\sigma$ is the stellar velocity dispersion. The structural parameters of Milky Way clusters (Harris 1996, 2010) do seem to support this idea, as two of the systems which host PNe have extremely high encounter rates (NGC 6441 has the second highest rate of all Galactic GCs, and M15’s rate ranks as seventh), and three of the four rank in the top half of clusters. Moreover, this result is not simply due to the clusters having more stars: if one calculates the mass-specific encounter rates of the Milky Way clusters, then again, three of the four clusters hosting PNe appear in the top half of the list. The statistics of only four objects are poor, but the numbers do suggest a connection between stellar encounters and PN formation.

Unfortunately, our emission-line survey of M31’s GC system does not yet allow us to increase the statistics significantly. Although over 250 of M31’s GCs have structural measurements (Barmby et al. 2007; Peacock et al. 2010), only 1 of the old clusters listed in Table 4 are included in that number. Interestingly, if we assume that the clusters are in virial equilibrium (so that we can approximate the encounter rate using $\Gamma \propto \rho_0^2 r_i^3$), then the cluster in question (B115-G177, which contains our best PN candidate) has a value of $\Gamma$ that ranks in the top $\sim 25\%$ of M31 systems. This again is suggestive, but it cannot be considered definitive until the other systems listed in Table 4 are surveyed.

Alternatively, we can attempt to explore the frequency of stellar encounters using X-ray emission as a proxy for encounter rate. Pooley et al. (2003) have shown that in Galactic GCs, there is an excellent correlation between $\Gamma$ and the number of low-mass X-ray binaries (LMXBs). If each LMXB had the same luminosity, we could test the PN binary-formation hypothesis by searching for a correlation between PN presence and X-ray brightness. Jacoby et al. (1997) did this experiment in the Milky Way, where each individual X-ray source can be identified. This led the authors to suggest that binaries were responsible for the cluster PNe.

In M31, one cannot resolve the individual X-ray sources within each cluster, and counting the total X-ray emission from a GC is not the same as measuring its total LMXB population. In fact, the large range of luminosities possible for LMXBs makes any connection between X-ray luminosity and binary population tenuous at best. In our survey, $\sim 15\%$ of the GCs have X-ray sources, but only one appears in Table 4 (Stiele et al. 2011). Consequently, X-ray emission in M31 clusters does not appear to present any evidence for the PN binary formation hypothesis.
Figure 9. The planetary nebula luminosity function for the bulge of M31 (black points with error bars). These data, which extend over nearly 5 mag, represent the deepest M31 PNLF currently available. The solid line shows the model PNLF (an exponential with a bright-end cutoff) that was adopted by Ciardullo et al. (1989). The magnitudes of the clusters PNe are marked: Milky Way PNe on the lower row, and M31 PNe on the upper row. The red circles, blue triangles, and tan squares represent PN candidates in old confirmed clusters, young clusters, lower row, and M31 PNe on the upper row. The red circles, blue triangles, and tan squares represent PN candidates in old confirmed clusters, young clusters, and candidate globular clusters, respectively.

(A color version of this figure is available in the online journal.)

5.3. The Luminosities of the Candidates

Figure 9 displays the [O III] $\lambda$5007 magnitudes of PNe associated with Milky Way and M31 clusters. From the figure, it is clear that most of the clusters found in our spectroscopic survey are far fainter than those discovered via narrow-band or counter-dispersed imaging. This is simply a consequence of the technique; slit spectroscopy reduces the sky background enormously, allowing us to probe a region of M31’s PN luminosity function that is undetectable by other methods.

The more salient feature of the diagram is the distribution of relative PN luminosities. The systems of GCs in the Milky Way and M31 each contain a lone bright PN candidate; the remaining objects are extremely faint, in a regime where the luminosity function of LMC PNe is increasing exponentially (Reid & Parker 2010). This is expected if most faint PNe have slowly evolving central stars embedded in freely expanding nebulae (Henize & Westerlund 1963). In GCs, however, we might expect the PNLF to be distorted, as the absence of intermediate mass stars might result in a deficit of intermediate luminosity PNe. Thus far, however, there is no evidence for this effect: according to a Kolmogorov–Smirnov test, the combined luminosity function of PNe in Milky Way and M31 GCs is fully consistent with the curve displayed in Figure 9. Of course, the numbers involved are small, but to date, there is no reason to reject the hypothesis that the PNe of GCs obey the simple law proposed by Ciardullo et al. (1989).

5.4. The Observational Challenge

For Galactic clusters, searching for PNe is relatively straightforward. As demonstrated by Jacoby et al. (1997), one can use the classic on-band/off-band technique to detect [O III] $\lambda$5007 over almost the entire PNLF. Moreover, one can resolve both the cluster stars (except near the cluster center) and, importantly, the nebula. These two factors enable easy detection of emission-line objects having the morphological characteristics of a PN, even at very low surface brightnesses. Furthermore, relative to an extragalactic survey, cluster classifications are far more reliable, as are the velocity measurements for both the PN and the cluster.

In contrast, attempts to identify PNe in other galaxies are faced with a host of complications. Among these are:

Mimics. Objects other than PNe (e.g., H II regions, SNRs, and diffuse emission) can have similar spectral signatures over the limited wavelength range of the WIYN Bench Spectrograph and its 740 lines mm VPH grating. This problem is partially technical, as many modern spectrographs offer more complete spectral coverage at comparable resolution, allowing better discrimination against potential mimics. Yet even in the Milky Way, PN classifications can be controversial (e.g., Viironen et al. 2009; Frew & Parker 2010) and PN candidates are constantly being re-evaluated. The limited information available on extragalactic objects only exacerbates this problem.

Spectral resolution and sensitivity. These instrumental parameters are probably the most critical factors for successfully and definitively finding PNe in extragalactic GCs. As described above, our ability to define the velocity (and the velocity dispersion) of the underlying star cluster severely limited our ability to exclude chance superpositions. We were fortunate that the literature provided an excellent source of velocities for many of our objects. For searches beyond M31, $\lesssim$3 km s$^{-1}$ velocity measurements will not always be available. Similarly, sensitivity becomes increasingly important at larger distances, both for determining cluster velocities and for probing the faint end of PNLF. The study in NGC 4472 (Peacock et al. 2012) only reached 2.5 mag down the PNLF; had we not gone far beyond this limit in M31, we likely would not have identified any PN candidates. Finally, resolution is also a helpful factor in this type of survey, both for the detection of PN emission, and for eliminating mimics such as SNRs and nova shells, which will have broad emission lines. Again, this is a technical issue where large telescopes can dramatically advance studies like this one.

Spectral aperture (slit width, fiber size). Our fiber diameter was limited to 3″, which is a reasonable match to the half-light radius of most M31 clusters. Still, these fibers do not sample all of the cluster light, and outlying PN could be overlooked, either because they fall entirely outside the fiber, or near the fiber limits, where flux is lost due to the effects of seeing. One could, of course, choose to use a large fiber or slit size for the observation (though at WIYN, the largest fiber size is 3″), but this would reduce the signal-to-noise of the measurement by admitting more sky and galactic background. This problem is ameliorated when going to more distant galaxies, though again at the cost of a higher galactic background and a loss of sensitivity due to the greater distance.

Multiple objects along the line of sight. When observing a distant galaxy, there is a finite probability that two unrelated objects will fall within the same spectroscopic aperture. This problem becomes worse as the distance increases, as a given fixed aperture represents a broader spatial swath of the galaxy. To compensate for this effect, one needs better velocity measurements so that unrelated objects can be discriminated.

In the future, searches for PNe in extragalactic GCs should be more productive as many of these challenges can be overcome with technological advancements. For example, the M31 problem becomes relatively easy with the high signal-to-noise spectra produced by an extremely large (25–40 m class) telescope (ELT) equipped with a multiobject, dual-channel, medium-resolution spectrograph. Similarly, adaptive optics on ELTs...
6. CONCLUSIONS

We have demonstrated that it is possible to identify PN candidates in distant GCs using spectroscopy around the [O III] λ5007 emission line. The principal difficulty in this approach lies in confirming that the candidates are, indeed, associated with the cluster. This requires precise radial velocity measurements, both for the emission line and the underlying stellar continuum. The better the velocity resolution of the survey, the easier it is to separate embedded PNe from chance superpositions, and to distinguish a cluster-bound PN from other unrelated emission-line sources along the line of sight, such as H II regions, SNRs, and diffuse emission.

Of the 270 M31 GC candidates observed with sufficient velocity precision, 5 show evidence for a candidate PN. Given the luminosity limits of the survey, the uncertainties in the velocity measurements, and the potential for confusion with other emission-line sources, this result is marginally consistent with the rate of PNe found in Milky Way clusters, i.e., 3 or 4 in 130 clusters, and the upper limit found in a survey of GCs around NGC 4472. This rate argues that less than one-quarter of the stars in old clusters form PNe (Jacoby et al. 1997). These numbers are also marginally consistent with the binary hypothesis for PN formation, which is about four times higher than the single star production rate in old clusters (Moe & De Marco 2006).

At this time we cannot say how many cluster-associated PNe have been formed from binary interactions. Only one M31 PN candidate is embedded in a cluster whose structural parameters are known, but based on that cluster’s properties, and on the properties of the Milky Way’s PN clusters, it appears that the binary evolution scenario is a viable hypothesis to explain all GC PNe. High resolution imaging would help confirm the existence of our PN candidates, and provide structural information on the host clusters.

In addition, we identified five PN candidates among the young clusters in our sample, a number that is much higher than that expected from the luminosity specific stellar death rate. These are likely superpositions; most of the young systems surveyed have large velocity uncertainties, and the similarity between their kinematics and that of the underlying disk make it difficult to identify superposed objects.

Finally, we emphasize that the M31 objects listed in Table 4 are PN candidates only. HST narrow-band images are needed to confirm their existence, especially for those objects within young clusters. However, once confirmed, these targets represent a new source of material for understanding the physics of PN formation, and the chemistry of their parent clusters.

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