POSSIBLE SUBGROUPS OF GLOBULAR CLUSTERS AND PLANETARY NEBULAE IN NGC 5128

Kristin A. Woodley and William E. Harris

1 Department of Physics & Astronomy, University of British Columbia, Vancouver BC V6T 1Z1, Canada; kwoodley@phas.ubc.ca
2 Department of Physics & Astronomy, McMaster University, Hamilton ON L8S 4M1, Canada; harris@physics.mcmaster.ca

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ABSTRACT

We use recently compiled position and velocity data for the globular cluster and planetary nebula subsystems in NGC 5128, the nearby giant elliptical, to search for evidence of past dwarf–satellite accretion events. Beyond a 10’ (∼11 kpc) radius in galactocentric distance, we find tentative evidence for four subgroups of globular clusters and four subgroups of planetary nebulae. These each have more than four members within a search radius of 2’ and internal velocity dispersion of <40 km s⁻¹, typical parameters for a dwarf galaxy. In addition, two of the globular cluster groupings overlap with two of the planetary nebula groupings, and two subgroupings also appear to overlap with previously known arc and shell features in the halo light. Simulation tests of our procedure indicate that the probability of finding false groups due to chance is <1%.

Key words: galaxies: elliptical and lenticular, cD – galaxies: individual (NGC 5128) – galaxies: interactions – galaxies: star clusters: general – globular clusters: general – planetary nebulae: general

1. INTRODUCTION

In the last decade or so, the presence of stellar streams within nearby galaxies has provided direct evidence for the continual build-up of massive galaxies from the accretion of small neighboring satellites. For example, in the Milky Way, there is the Sagittarius stream (Ibata et al. 1997, 2001b; Majewski et al. 2003; Martínez-Delgado et al. 2004), and in M31, a number of new streams have been recently discovered within the Pan-Andromeda Archeological Survey (McConnachie et al. 2009), adding to the list of already known streams in that galaxy (Ibata et al. 2001a). In addition, striking surface brightness features tracing a galaxy’s merger history have been found in NGC 5907 (Shang et al. 1998), NGC 891 (Mouhcine et al. 2010), NGC 5093 (Martínez-Delgado et al. 2008), NGC 253 and NGC 5236 (Malin & Hadley 1997), and UGC 10214 (Forbes et al. 2003), among others. Past work has shown that it is possible to use streams to trace the orbits of satellite galaxies that had merged with the Milky Way in the distant past (Lynden-Bell & Lynden-Bell 1995; Yoon & Lee 2002). Lynden-Bell & Lynden-Bell (1995) suggest that the tidal debris stripped out of the parent dwarf galaxy will not undergo much dynamical friction because its mass content will be low.

In systems beyond our Local Group galaxies, finding these traces of old satellites becomes more difficult. But in addition to the field-star-integrated light, it is possible to use other old objects such as globular clusters (GCs) and planetary nebulae (PNe) to provide evidence for the presence of accretion remnants (Forte et al. 1982; Muzzio 1987; Côté et al. 1998, 2002; Hilker et al. 1999). Also, Pipino et al. (2007) have modeled the GC assembly history in massive galaxies, and showed that in addition to the GCs that formed along with the galaxy halo, a significant fraction of GCs that make up the massive galaxies were likely accreted from dwarf galaxies in later times. Indeed, subgroups of GCs have been found within the halos of massive galaxies or have been associated with the stellar streams in the Sagittarius stream (Ibata et al. 1994, 1997; Bellazzini et al. 2003) and in M31 (Perrett et al. 2003; Mackey et al. 2010).

For our search, we target NGC 5128 (Centaurus A) which is a giant elliptical galaxy at a distance of 3.8 ± 0.1 Mpc (Harris et al. 2010). While this galaxy is quite close, it is still beyond the distance where detecting faint stellar streams is an easy task. Previous work by Malin et al. (1983) and Peng et al. (2002) has shown that there are existing complex shell structures that surround the central regions out to 15 kpc, attributed to the many accretions of small neighboring galaxies. There are also H i shells (Schiminovich et al. 1994), and a prominent warped dust lane (Graham 1979) is also present in the central region where gas and dust are settling into the central potential well. There is evidence for young stars (Rejkuba et al. 2001, 2002; Ellis et al. 2009) that may be aligned with the radio jet. This star formation could have been triggered by the jet colliding with cloud material brought into NGC 5128 via a merging event.

NGC 5128 has 607 confirmed GCs, via radial velocity measurements (van den Bergh et al. 1981; Hesser et al. 1984, 1986; Harris et al. 1992; Peng et al. 2004b; Woodley et al. 2005; Rejkuba et al. 2007; Beasley et al. 2008; Woodley et al. 2010a, 2010b) and/or resolved images from the Advanced Camera for Surveys on the Hubble Space Telescope (Harris et al. 2006; Mouhcine et al. 2010a). Of these, 563 have measured radial velocities. Their mean measurement uncertainty is 42 km s⁻¹, though the range of uncertainties is quite large, with 96% of the population having uncertainties <200 km s⁻¹. The currently known GCs are distributed in galactocentric radius out to 50’ (where 1’ ~ 1.1 kpc at the distance of NGC 5128), although the inner 5’ is sparsely populated because of the obscuration of the well-known central dustlane. There are also 780 confirmed PNe with positional and radial velocity data (Peng et al. 2004a), which can be used as stellar tracers in the same way.

2. GROUP IDENTIFICATION TECHNIQUE

2.1. Globular Cluster Observational Data Set

From both the GC and PNe databases, we attempt to identify genuine subgroups in the classic way by looking for objects that are close to each other in both position and velocity. Our basic search approach follows that of Perrett et al. (2003) for the GCs in M31. We look first at the GCs. Here the NGC 5128 GC data face us with the additional difficulty beyond the situation in M31: not only are the positions and velocities seen in projection, but also the velocity measurement uncertainties (averaging more
than 40 km s\(^{-1}\)) are usually larger than the expected \(~20\) km s\(^{-1}\) true, physical velocity dispersion of a typical satellite dwarf in the Local Group (Geha et al. 2010). For this reason, we view our present work as only a preliminary step toward finding genuine physical subgroups. For the same reason, we suggest that at this stage only rather simple group-finding search procedures are justified. Logical next steps would include higher precision velocity data and imaging to search for faint surface brightness features.

GC metallicity or color might in principle be additional search criteria, as it may be expected that GCs within one accreted system share similar enrichment processes, but these properties are less useful in practice. In our sample of GCs, the metallicities are either from a color transformation or simply based on a color division which we take from Woodley et al. (2007, 2010a, 2010b). We have classified the GCs as being either metal-poor or blue ([Fe/H] < −1.0) or as metal-rich or red ([Fe/H] ≥ −1.0) following previous work on the GC system of NGC 5128 (Harris et al. 2004; Woodley et al. 2005, 2007) or as metal-rich or red if \((B − I) ≥ 2.072\) and metal-poor or blue if \((B − I) < 2.072\), following Peng et al. (2004b). The division between red and blue GCs is thus not homogeneously determined and depends on a variety of methods as well as a number of different photometric studies. Of these GCs, 291 are classified as metal-poor, 292 as metal-rich, and 24 GCs have insufficient photometry for any of the above transformations. In addition, while there is evidence that the metallicities, on average, of GCs in dwarf galaxies are more metal-poor than in more massive galaxies (Sharina et al. 2010), there is evidence that a range of metallicities of GCs can exist within a single dwarf galaxy, for example, in the dwarf galaxies IC10 and UGCA86 (Sharina et al. 2010). Also, there can exist a spread in the metallicities of the dwarf galaxies themselves (see the review of Mateo 1998). This information, taken together, makes it quite difficult to incorporate a defined range of acceptable color or metallicity within a subgroup as a search parameter; we note that Perrett et al. (2003) also ignored metallicity as a search parameter.

We searched for GC subgroups in the outer regions of NGC 5128, beyond 10′. Inside this radius, there would be a high fraction of false subgroups because the density of objects is high, and the biggest source of finding false subgroups is due to the accidental two-dimensional projection of objects that are actually far from the line of sight. Additionally, it is the outer halo that should still preserve coherent traces of accreted satellites, because the much larger dynamical times there prevent them from being fully phase-mixed (Bullock & Johnston 2005).

As mentioned above, we use essentially a nearest-neighbor approach with two linking criteria. For each GC outside a 10′ galactocentric distance, we calculate the separation in the projected linear distance between it and all other GCs in the catalog (the boundary can therefore extend slightly inward of 10′) and group the GCs if these are within our imposed linking length. We also included the GC velocity and velocity uncertainties in our search such that two GCs would match if the range of its velocity plus or minus its velocity uncertainty can be subtracted from another objects velocity such that their absolute difference is less than 20 km s\(^{-1}\). For example, objects with velocities 500 ± 30 km s\(^{-1}\) and 460 ± 20 km s\(^{-1}\) would be linked. To help avoid false group detections based on poorly measured velocities, we only considered GCs whose velocity uncertainties were less than an imposed limit. We also combined groups that were found to have common members, which allows for groups that may exist in a chain-like structure.

A search using a spatial linking length of 1′ did not yield any subgroups with more than four members. When we increased the linking length to 2′, which is a reasonable size for a subgroup from a dwarf galaxy, we did indeed find plausible subgroups. With a linking length of 2′, as well as allowing for velocity uncertainties of up to 40 km s\(^{-1}\), we detected a plausible subgroup of GCs including six group members. When we include GCs in our search that have measured velocity uncertainties up to 50 km s\(^{-1}\), we increase the number of group members by one, and call this a possible group of seven members, labeled GC 1. When we increase the allowed velocity uncertainty to 80 km s\(^{-1}\), we end up finding three additional subgroups, each consisting of five members, which we label groups GC 2, GC 3, and GC 4. Many of these are likely to be included simply because of the large velocity allowance, and we cannot be sure that these are all real groups. If we set our velocity uncertainty limit to 40 km s\(^{-1}\), but increase our linking length to 3′, we increase the number of members in our subgroup from six to ten (included as possible members of group GC 1). Many of these included GCs may not be real members. The possible subgroups are plotted in Figure 1 and are listed in Table 1 with columns of the GC ID, group ID, R.A. and decl. in J2000 coordinates, the [Fe/H] value, their galactocentric radius, \(R_{GC}\), and their measured radial velocity, \(\nu_r\), and associated uncertainty, \(\sigma_{\nu_r}\). The radial velocities and

![Figure 1](image-url)
uncertainties are weighted values determined from all previous measurements in the literature. These values are obtained from Woodley et al. (2007, 2010a, 2010b).

The image of NGC 5128 in Figure 1 was obtained with the Mosaic II optical CCD camera on the 4 m Blanco telescope at the Cerro Tololo Inter-American Observatory. It was graciously provided to us in its reduced form by Eric Peng with its reduction described in Peng et al. (2002). We smoothed the image using a 300 × 300 pixel box and subtracted it from the original image. To enhance the visibility of the low-surface brightness shells and arc structures and preserve some of the dominant bulge light, we added back 15% of the smoothed image. We find that in a general sense, the candidate subgroups that we have identified fall in the same radial zones of galactocentric distance where the shells are found. However, a stronger indication of possible connections is seen along the isophotal major axis of the galaxy (35° and 215° E of N; Dufour et al. 1979). Toward the southeast (lower right in Figure 1), group GC 1 falls on the irregular plume of light, while on the opposite side to the northwest, group GC 3 falls on or close to the two of the visible arcs. The remaining two groups, GC 2 and GC 4, do not seem to be projected on any known surface brightness features.

2.2. Planetary Nebula Observational Data Set

We performed the same subgroup finding algorithm on the available PNe data in the literature. There are 780 PNe with radial velocity measurements (Peng et al. 2004a; Hui et al. 1995) in NGC 5128, which were detected by the [O iii] emission line. While there are no velocity uncertainties presented in the literature for the PNe, we have assumed a radial velocity uncertainty of 20 km s^-1 for each object, which is the typical rms velocity error presented in Peng et al. (2004a). Using our same subgroup finding criteria as for the GCs (linking length of 2', velocity difference of 20 km s^-1 plus the inclusion of the velocity uncertainties, at a minimum distance of 10' from the center of the galaxy for the central group member), we found four potential groups. These groups are plotted in Figure 1 and listed in Table 2 which provides their ID from Peng et al. (2004a), their group ID, R.A. and decl. in J2000 coordinates, the galactocentric radius, , their radial velocity measurement, , and assumed 20 km s^-1 velocity uncertainty. Out of the four subgroups of PNe discovered, three have group sizes of 5–6, while the remaining group has nine members. These groups have been labeled PNe 1, PNe 2, PNe 3, and PNe 4.

2.3. Properties of Subgroups

The mean velocity and rms velocity dispersions for each group are listed in Table 3. The velocity dispersion for each subgroup ranges from 29 to 43 km s^-1 for the GC subgroups and from 12 to 24 km s^-1 for the PNe subgroups, within a reasonable range for a plausible group.

Our results indicate that there are three possible overlaps between the GC and the PN subgroups. These are PNe 1 with GC 2 (Group 1), PNe 2 with GC 3 (Group 2), and PNe 3 with GC 4 (Group 3). Examining the average velocities for each of these subgroups, the average radial velocity differences are Δ(⟨vGC⟩ − ⟨vPNG⟩) = 39 km s^-1 for Group 1, −136 km s^-1 for Group 2, and 0 km s^-1 for Group 3. The difference in average velocities for Groups 1 and 3 are within the expected uncertainty range of the measured velocities, which is 42 km s^-1.

| ID     | Group ID | R.A. (J2000) | Decl. (J2000) | [Fe/H] | Rgc (″) | v_r (km s^-1) | σ_v_r (km s^-1) |
|--------|----------|--------------|---------------|--------|---------|---------------|-----------------|
| GC0067 | GC 1     | 13:24:51.49  | −43:12:11.1   | −1.17  | 12.86   | 624           | 13              |
| GC0083 | GC 1     | 13:24:56.08  | −43:10:16.4   | −2.46  | 10.79   | 687           | 31              |
| GC0106 | GC 1     | 13:25:01.83  | −43:09:25.4   | −1.42  | 9.52    | 688           | 16              |
| GC0114 | GC 1     | 13:25:03.37  | −43:11:39.6   | −1.29  | 11.41   | 605           | 46              |
| GC0117 | GC 1     | 13:25:04.48  | −43:10:48.4   | −0.32  | 10.54   | 626           | 22              |
| GC0122 | GC 1     | 13:25:05.46  | −43:14:02.6   | −1.37  | 13.51   | 679           | 13              |
| GC0119 | GC 1     | 13:24:55.31  | −43:10:39.3   | −0.35  | 11.19   | 656           | 27              |
| GC0422 | GC 1     | 13:25:03.28  | −43:08:14.4   | −1.65  | 8.37    | 690           | 31              |
| GC0491 | GC 1     | 13:24:54.98  | −43:11:36.9   | −0.22  | 12.05   | 670           | 19              |
| GC0492 | GC 1     | 13:25:56.61  | −43:12:23.6   | −1.94  | 12.59   | 713           | 28              |
| GC0504 | GC 1     | 13:25:08.94  | −43:08:53.7   | −1.96  | 8.46    | 678           | 26              |
| GC0534 | GC 2     | 13:26:02.25  | −43:08:55.6   | −0.65  | 10.03   | 457           | 38              |
| GC0598 | GC 2     | 13:26:09.52  | −43:08:52.4   | −0.41  | 10.88   | 482           | 67              |
| GC0379 | GC 2     | 13:26:12.82  | −43:09:09.2   | −0.49  | 11.50   | 545           | 60              |
| GC0544 | GC 2     | 13:26:17.27  | −43:09:58.0   | −0.05  | 12.65   | 473           | 39              |
| GC0393 | GC 2     | 13:26:22.08  | −43:10:10.7   | −1.20  | 12.79   | 505           | 78              |
| GC0534 | GC 3     | 13:25:55.35  | −42:53:40.2   | −2.30  | 9.04    | 347           | 41              |
| GC0590 | GC 3     | 13:25:46.96  | −42:52:34.0   | −0.95  | 9.28    | 355           | 66              |
| GC0532 | GC 3     | 13:25:54.79  | −42:52:57.1   | −0.33  | 9.59    | 399           | 32              |
| GC0341 | GC 3     | 13:25:58.91  | −42:53:18.9   | −1.34  | 9.70    | 410           | 20              |
| GC0334 | GC 3     | 13:25:56.59  | −42:51:46.6   | −0.73  | 10.77   | 403           | 16              |
| GC0518 | GC 4     | 13:25:25.36  | −42:49:27.5   | −1.55  | 11.70   | 589           | 63              |
| GC0163 | GC 4     | 13:25:15.79  | −42:49:15.1   | −1.44  | 12.09   | 534           | 52              |
| GC0516 | GC 4     | 13:25:23.31  | −42:48:47.7   | −0.54  | 12.38   | 526           | 11              |
| GC0220 | GC 4     | 13:25:30.72  | −42:48:13.4   | −1.88  | 12.94   | 484           | 47              |
| GC0511 | GC 4     | 13:25:18.29  | −42:47:52.4   | −0.65  | 13.39   | 487           | 39              |

Notes.

a Included if velocity uncertainty cut-off increased from 40 km s^-1 to 50 km s^-1.
b Included member in the group if linking length increased from 2' to 3'.
note that Peng et al. (2008) show that the range of assuming that the galaxy is spherically shaped with a 2

Sections 2.4 and 3.3, we analyze the probability that the appear to have strong velocity connections, and are likely either

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MV dwarf galaxies spans 1–20. With these inputs, we obtain

subgroups. Considering first the GC subgroups, we

∼−6 GCs or 6 PNe, typical of what we have found in our

Table 2

Possible Planetary Nebulae Subgroups in NGC 5128

| ID   | Group ID | R.A. (J2000) | Decl. (J2000) | Rgc (′) | νv (km s⁻¹) | σνv (km s⁻¹)² |
|------|----------|--------------|--------------|---------|-------------|---------------|
| ctrl513 | PNe 1 | 13:26:14.26 | −43:08:22.5 | 11.18 | 480 | 20 |
| f08p10 = 5506 | PNe 1 | 13:26:06.19 | −43:09:06.2 | 10.63 | 462 | 20 |
| 5506 | PNe 1 | 13:26:13.01 | −43:06:45.0 | 10.01 | 439 | 20 |
| f07p06 | PNe 1 | 13:26:11.33 | −43:09:57.3 | 11.89 | 421 | 20 |
| f07p08 | PNe 1 | 13:26:06.87 | −43:07:36.0 | 9.65 | 476 | 20 |
| f08p9 | PNe 1 | 13:25:56.04 | −43:09:24.7 | 9.76 | 439 | 20 |
| f17p34 | PNe 2 | 13:26:11.29 | −42:52:39.6 | 11.65 | 535 | 20 |
| f18p46 | PNe 2 | 13:26:10.83 | −42:54:01.5 | 10.64 | 527 | 20 |
| f18p51 | PNe 2 | 13:26:07.42 | −42:54:01.4 | 10.18 | 530 | 20 |
| f18p55 = 1217 | PNe 2 | 13:26:02.57 | −42:53:07.1 | 10.26 | 516 | 20 |
| f18p74 = 1303 | PNe 2 | 13:26:05.35 | −42:51:31.3 | 11.84 | 522 | 20 |
| 5106 | PNe 2 | 13:26:11.57 | −42:55:37.7 | 9.75 | 506 | 20 |
| 5108 | PNe 2 | 13:26:09.16 | −42:55:20.1 | 9.56 | 513 | 20 |
| f18p69 = 4031 | PNe 2 | 13:25:56.78 | −42:53:50.4 | 9.05 | 499 | 20 |
| f18p70 | PNe 2 | 13:25:58.98 | −42:53:39.0 | 9.44 | 517 | 20 |
| f18p15 | PNe 3 | 13:25:41.55 | −42:45:41.5 | 15.67 | 519 | 20 |
| f18p16 | PNe 3 | 13:25:38.18 | −42:46:04.4 | 15.20 | 501 | 20 |
| f18p17 | PNe 3 | 13:25:39.18 | −42:45:24.2 | 15.89 | 534 | 20 |
| f18p18 | PNe 3 | 13:25:34.32 | −42:46:11.5 | 15.01 | 531 | 20 |
| f18p40 | PNe 3 | 13:25:40.29 | −42:43:44.0 | 17.57 | 553 | 20 |
| f18p26 | PNe 3 | 13:25:26.79 | −42:47:36.5 | 13.54 | 507 | 20 |
| ctr264 | PNe 4 | 13:24:50.38 | −42:53:22.6 | 10.33 | 557 | 20 |
| f19p06 | PNe 4 | 13:24:45.76 | −42:51:30.0 | 12.31 | 588 | 20 |
| f19p07 | PNe 4 | 13:24:44.04 | −42:52:09.9 | 12.01 | 538 | 20 |
| 4608 | PNe 4 | 13:24:49.87 | −42:52:46.8 | 10.85 | 597 | 20 |
| ctrl22 | PNe 4 | 13:24:53.26 | −42:53:26.8 | 9.94 | 566 | 20 |

Note. a For all PNe, we have assumed a radial velocity uncertainty of 20 km s⁻¹.

Table 3

Properties of the Subgroups

| Group ID | Vmean (km s⁻¹) | σνv (km s⁻¹) |
|----------|-----------------|--------------|
| GC 1a    | 651             | 25           |
| GC 2     | 492             | 26           |
| GC 3     | 382             | 19           |
| GC 4     | 524             | 34           |
| PNe 1    | 453             | 21           |
| PNe 2    | 518             | 11           |
| PNe 3    | 524             | 17           |
| PNe 4    | 569             | 21           |

Note. a These values have been calculated using the seven probable group members of GC 1 using a linking length of 2'.

for the average GC. The subgroups of Group 2, however, do not appear to have strong velocity connections, and are likely either not real groups or are overlapping by chance in projection. In Sections 2.4 and 3.3, we analyze the probability that the overlapping can occur by chance.

In very rough terms we can estimate the total luminosity of the underlying satellite galaxy that would consist of either ~6 GCs or 6 PNe, typical of what we have found in our subgroups. Considering first the GC subgroups, we assume a specific frequency, Sν, which is the number of GCs per unit Mν = −15 galaxy luminosity (Harris & van den Bergh 1981). We adopt Sν = 3, typical for a normal faint galaxy, though note that Peng et al. (2008) show that the range of Sν for dwarf galaxies spans 1–20. With these inputs, we obtain Mν = −15.8 mag and a surface brightness of 24 mag arcsec⁻² assuming that the galaxy is spherically shaped with a 2’ radial extent. For a PN subgroup of ~6 members, we can estimate the bolometric luminosity of the underlying satellite galaxy with the luminosity specific PN number, α = NPN/Ltot, where NPN is the total number of PNe and Ltot is the total luminosity (Jacoby 1980). Ciardullo et al. (2005) show α0.5 ∼ 2 × 10⁻⁵ for galaxies in the range of M7 = −14 to −16 (please see their Figure 1). However, in the case of NGC 5128, the PNe data extend at least 1.5 mag down the luminosity function (Peng et al. 2004a), and we thus estimate α0.5 ∼ 11.5 × 10⁻⁹, to obtain Ltot = 5.2 × 10⁸ L⊙. We obtain Mν = −16.2 mag after a bolometric correction of −0.85 (Buzzoni et al. 2006). Assuming the galaxy is spherical with a radial extent of 2’, we obtain a surface brightness of 24 mag arcsec⁻². Both estimates of the surface brightness of a potential underlying dwarf galaxy are very rough guides due to the input assumptions, and we do not think that this test is capable of ruling out whether or not we should see these structures in previously obtained deep images of NGC 5128. We appear to be finding mild traces of substructure that are not hugely above the statistical noise.

2.4. Scrambling the Velocities

Our first step toward assessing how real our candidate groups in Table 1 are is through a non-parametric test. By taking our GC positions in two-dimensional space, we randomly assign each GC a unique and real velocity and velocity uncertainty from the GC catalog. We then perform our search for subgroups with a linking length of 2’, a velocity difference of 20 km s⁻¹ plus the inclusion of velocity uncertainties up to 40 km s⁻¹, at a minimum distance of 10’ from the center of the galaxy for the central group member. Out of 1000 trials, we found that 23.2% of cases found one group containing at least four members. In
1.8% of the cases, the trials found two groups with at least four members, and in one case (0.1%), there were three groups found. This indicates that it is likely that one of the GC candidate subgroups may be a false group. We did not find a case, however, in which four candidate groups arose with this methodology.

We examined closely the groups in this test that had more than one group per trial. In the 18 cases that found two groups, there were two trials in which the groups overlapped in projected space. In the trial consisting of three groups, two of these groups overlapped. This indicates that while finding more than one group in a trial was rare, when it did occur there was an approximately 15% chance they would overlap. Since these groups were all from the GC population, none of the subgroups that overlapped had similar average radial velocities.

Finally, we randomly assigned each GC a unique and real velocity and velocity uncertainty from the GC catalog, but this time, we incorporated GCs with velocity uncertainties up to 80 km s\(^{-1}\). Our results indicate that out of 1000 trials, at least four false groups were found in 1.5% of the cases. This simple test indicates that it is not likely that all four GC subgroups are false, but it is quite probable that some may indeed by false.

3. SIMULATING GLOBULAR CLUSTER SYSTEMS

3.1. Searching for False Subgroups

Here, we assess how often our search procedure would turn up false groups of similar apparent quality from purely random distributions. It is similarly important to examine how often our procedure would successfully find a real subgroup within the data.

To carry out tests of the procedure, we generated simulated GC systems in which the particles are located randomly within a spherically symmetric space distribution following a three-dimensional density power law $\rho \sim r^{-\alpha}$, with $n(3D) = 2.5$ for the metal-poor GCs and $n(3D) = 3.0$ for the metal-rich clusters. The particle velocities were assigned randomly in a Gaussian distribution with a dispersion of 150 km s\(^{-1}\) for all GCs, and their individual measurement uncertainties were randomly distributed uniformly from 5 to 80 km s\(^{-1}\). All of these parameters mimic the NGC 5128 GC system.

For 1000 realizations, each GC system consisted of 550 objects, with 50% red and 50% blue subpopulations, which were projected from their real three-dimensional positions into two dimensions. We then searched for subgroups with our finding algorithm, as we have done for the observational data in Section 2.1. Our search criteria allowed objects to be group members only if they were within a projected length of 2′ from each other, have a velocity difference of <20 km s\(^{-1}\), exist outside of 10′ from the galaxy’s center, and have a velocity uncertainty less than 40 km s\(^{-1}\) for each member. All real group members were recovered as well as the inclusion of fake members in 103 of the simulations. In two of the simulations, some of the real group members were found with fake member interlopers, and in three of the simulations some of the group members were found with no fake interlopers detected. We therefore consider our detection method to be very successful as in more than 89% of cases, we were able to find our exact simulation group system and 10.3% of the time, we also found all group members, however with interlopers. When interlopers were present in the detected subgroups, 96.2% of these occurrences had only one interloper, while two interlopers were detected in the remaining cases. These results strongly suggest that at least some of our observationally detected subgroups are real and they cannot all simultaneously be false detections.

3.3. Testing the Probability of Random Overlapping Groups

Finally, we test whether our candidate subgroups might be smaller ones overlapped by projection purely by chance. To the simulated GC system as a whole, we add random subgroups consisting of four to six members whose members are confined within a 2′ region. These subgroups were randomly placed in the galaxy between 10′ and 50′ before being deprojected into two-dimensional space. Two groups were considered to overlap if any one of their members was within a small designated distance from any member of another group. The distance chosen did not significantly change our findings (considering differences between 0.1 and 2′), so we selected 0.5.

We performed seven simulations, each consisting of a different number of subgroups placed in the galaxy, which increased linearly from two subgroups up to eight subgroups. For each of these simulations, we examined, over 1000 trials, how many times these subgroups overlapped. The number of...
and a velocity uncertainty less than 50 km s$^{-1}$ GCs and PNe separately in the analysis below. et al. 2003) and search for evidence of stellar streams using the satellites. To do this, we use a friendless algorithm (Merrett et al. 2006), while a recent radial velocity measurement indicates that this object may be a star (Woodley et al. 2010a), and it is because of this low radial velocity measurement that this object is identified. GC0578 may indeed be friendless, but it is not possible to use one GC to indicate evidence for a stellar stream. Using $N = 10$ and $\sigma_N = 3$ yields seven friendless GCs (GC0216, GC0249, GC0325, GC0506, GC0577, GC0578, and GC0580).

We conduct the same analysis with the PNe dataset using $\sigma_N = 4$ and find no friendless objects when $N = 30$, one when $N = 20$ (f05p02), and six when $N = 10$ (4012, 4285, 5602, f05p02, f18p28, and f42p10). Using $N = 10$ and $\sigma_N = 3$ yields 20 friendless PNe (4012, 4128, 4285, 4417, 4511, 5203, 5601, 5602, 5617, 6104, f04p1, f05p02, f08p50 = 3002, f14p016, f18p28, f18p65 = 1208, f18p67 = 4023, f18p83, f42p10, and mosNEp4). The locations of the inner $\sim 15$ of these are shown in Figure 1.

The friendless objects that are located at the largest distances from the galaxy’s center are likely not indicators of streams. Rather, there are very few neighbors as the incompleteness of planetary nebulae and GCs is quite high beyond 20$^\circ$ (see the radial distribution as a function of azimuth for the GCs in Figure 8 of Woodley et al. 2010a and the distribution of the PN in Figure 2 of Peng et al. 2004a). This leaves only the inner 20$^\circ$ which can be explored for friendless objects, of which there are few (again, depending on the parameters chosen in the friendless algorithm). We list these objects with the suggestion that (at least) some of them may trace stellar orbits, and continued searches for stellar streams or orbital modeling are necessary to go beyond this preliminary work.

### 4. SEARCHING FOR STELLAR ORBITS

Work by Peng et al. (2002) shows a complex but faint shell structure threading the inner and mid-halo regions of NGC 5128. These shells have been attributed to the phase-wrapping of stars from accreted satellites. One particular blue elliptical arc was found to be associated with a young star cluster ($\gtrsim 350$ Myr), but aside from this one example, no stellar streams have been associated with GCs or PNe.

We have begun a search for evidence of stellar streams in NGC 5128 by probing the objects within the galaxy that may trace the stream. We use the available data for the GCs and the PNe, which may be stripped along with the stellar stream material during galaxy interactions. If these objects are located, they can be used to identify the possible orbits of accreted satellites. To do this, we use a friendless algorithm (Merrett et al. 2003) and search for evidence of stellar streams using the GCs and PNe separately in the analysis below.

For each object in our sample with a measured radial velocity and a velocity uncertainty less than 50 km s$^{-1}$ (totaling 411 GCs and 780 PNe), we have found its $N$ nearest neighbors. For those $N$ neighbors, we have calculated their mean velocity $v_{\text{mean}, N}$ and their velocity dispersion, $\sigma_N$. We have classified the central object as friendless if its velocity is more than $n \times \sigma_N$ from $v_{\text{mean}, N}$. Varying the $N$ parameter does not seem to significantly alter the results. We do find varying the $\sigma_N$ parameter from three to four changes the number of friendless objects by a few, while varying $\sigma_N$ from two to three does change the number of objects significantly.

Taking a conservative approach and using $\sigma_N = 4$, we find no friendless GCs when $N = 30$, one when $N = 20$ (GC0258), and one when $N = 10$ (GC0578). GC0258 will not be considered further as it was classified as a resolved GC in Harris et al. (2006), while a recent radial velocity measurement indicates that this object may be a star (Woodley et al. 2010a), and it is because of this low radial velocity measurement that this object is identified. GC0578 may indeed be friendless, but it is not possible to use one GC to indicate evidence for a stellar stream. Using $N = 10$ and $\sigma_N = 3$ yields seven friendless GCs (GC0216, GC0249, GC0325, GC0506, GC0577, GC0578, and GC0580).

We conduct the same analysis with the PNe dataset using $\sigma_N = 4$ and find no friendless objects when $N = 30$, one when $N = 20$ (f05p02), and six when $N = 10$ (4012, 4285, 5602, f05p02, f18p28, and f42p10). Using $N = 10$ and $\sigma_N = 3$ yields 20 friendless PNe (4012, 4128, 4285, 4417, 4511, 5203, 5601, 5602, 5617, 6104, f04p1, f05p02, f08p50 = 3002, f14p016, f18p28, f18p65 = 1208, f18p67 = 4023, f18p83, f42p10, and mosNEp4). The locations of the inner $\sim 15$ of these are shown in Figure 1.

The friendless objects that are located at the largest distances from the galaxy’s center are likely not indicators of streams. Rather, there are very few neighbors as the incompleteness of planetary nebulae and GCs is quite high beyond 20$^\circ$ (see the radial distribution as a function of azimuth for the GCs in Figure 8 of Woodley et al. 2010a and the distribution of the PN in Figure 2 of Peng et al. 2004a). This leaves only the inner 20$^\circ$ which can be explored for friendless objects, of which there are few (again, depending on the parameters chosen in the friendless algorithm). We list these objects with the suggestion that (at least) some of them may trace stellar orbits, and continued searches for stellar streams or orbital modeling are necessary to go beyond this preliminary work.

### 5. CONCLUSIONS

We have searched the GC and PN systems in the nearby giant elliptical galaxy NGC 5128 for evidence of stellar subgroups and stellar streams from merging events. Our results indicate that there may be up to four potential subgroups of GCs and four potential subgroups of PNe. Two of the PNe subgroups overlap with two of the GC subgroups in position and velocity. In order to improve the search for these subgroups in NGC 5128, we need higher precision radial velocity measurements to more concretely determine if these objects are grouped together.

By generating GC systems that mimic that in NGC 5128, we are able to assign the probability of our results being a chance encounter due to the projection of these objects onto a two-dimensional plane. The probability of finding a fake subgroup within the GC population is $<1\%$, while the probability of having a set of subgroups overlap is $\sim 4\%$. These results strongly suggest that at least some of these subgroups may indeed be real.

### Table 4

| $N$ Subgroups | Zero Overlap | One Overlap | Two Overlaps | Three Overlaps | Four Overlaps | Five Overlaps |
|---------------|-------------|------------|-------------|---------------|-------------|-------------|
|               | N Occurrences out of 1000 |            |             |               |             |             |
| N Subgroups   |            |            |             |               |             |             |
| 2             | 958        | 42         | 0           | 0             | 0           | 0           |
| 3             | 869        | 129        | 2           | 0             | 0           | 0           |
| 4             | 783        | 213        | 4           | 0             | 0           | 0           |
| 5             | 631        | 327        | 40          | 2             | 0           | 0           |
| 6             | 439        | 450        | 99          | 11            | 1           | 0           |
| 7             | 358        | 445        | 160         | 36            | 1           | 0           |
| 8             | 249        | 441        | 229         | 67            | 13          | 1           |

The chance of overlapping subgroups is $\sim 7\%$. Excluding Group 2, whose subgroups have very different average velocities, our results suggest that there may be two sets of overlapping subgroups, Groups 1 and 3. The probability of two sets of subgroups randomly overlapping with eight subgroups present is $23\%$. It is therefore not clear if these overlapping subgroups found in Groups 1 and 3 are real.
We have also searched for evidence of stellar streams by locating GCs and PNe that differ from its neighbors in velocity space using a friendless search algorithm. We present our findings as potential tracers; however, further work in orbital modeling as well as searches for very faint surface brightness features would be necessary beyond this point to further define the stellar streams.

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