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Williams, B. F., Ciardullo, R., von Hippel, T., & al., e. (2007). Virgo's Intracluster Globular Clusters as Seen by the Advanced Camera for Surveys. *The Astrophysical Journal*, 654(2). Retrieved from <https://commons.erau.edu/publication/272>

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VIRGO'S INTRACLUSTER GLOBULAR CLUSTERS AS SEEN BY THE ADVANCED CAMERA FOR SURVEYS

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Received 2006 June 21; accepted 2006 September 5

ABSTRACT

We report the discovery of four candidate intracluster globular clusters (IGCs) in a single deep *HST* ACS field of the Virgo Cluster. We show that each cluster is roughly spherical, has a magnitude near the peak of the Virgo globular cluster luminosity function, has a radial profile that is best fitted by a King model, and is surrounded by an excess of point sources that have the colors and magnitudes of cluster red giant stars. Despite the fact that two of our IGC candidates have integrated colors redder than the mean of the M87 globular cluster system, we propose that all of the objects are metal-poor, with $[M/H] < -1$. We show that the tidal radii of our intracluster globular clusters are all larger than the mean for Milky Way clusters and suggest that the clusters have undergone less tidal stress than their Galactic counterparts. Finally, we normalize our globular cluster observations to the luminosity of intracluster stars and derive a value of $S_N \sim 6$ for the specific frequency of Virgo intracluster globular clusters. We use these data to constrain the origins of Virgo's intracluster population and suggest that globular clusters in our intracluster field have a different origin than globular clusters in the vicinity of M87. In particular, we argue that dwarf elliptical galaxies may be an important source of intracluster stars.

Subject headings: galaxies: evolution — galaxies: star clusters — globular clusters: general

Online material: color figure

1. INTRODUCTION

The constituents of intracluster space can tell us a great deal about the history of galaxies and clusters. As a cluster forms, tidal interactions between galaxies and with the cluster potential affect the internal structure of galaxies, altering both their morphological and photometric properties (Butcher & Oemler 1978; Dressler 1980; Goto et al. 2003; Coenda et al. 2006; and many others). At the same time, these interactions also liberate material into intergalactic space, thus creating a fossil record of the encounters. By studying the composition, distribution, and kinematics of these orphaned

objects, we can examine the physics of tidal stripping, the distribution of matter in and around galaxies, and the initial conditions and history of cluster formation (Merritt 1984; West et al. 1995; Gregg & West 1998; Sommer-Larsen et al. 2005; and many others).

Intracluster globular clusters (IGCs) are an especially useful probe of these processes (West et al. 1995). As a globular cluster evolves, it preserves information about the time of its creation, the chemistry of the gas out of which it formed, and even the gravitational forces to which it has been exposed (see Ashman & Zepf 1998 and references therein). Consequently, a large sample of IGCs can be used to trace the history of galaxy interactions and

TABLE 1
MEASURED PARAMETERS FOR IGC CANDIDATES

| Property | IGC-1 | IGC-2 | IGC-3 | IGC-4 |
|--|-------------------|-------------------|-------------------|-------------------|
| α (J2000.0)..... | 12 28 04.78 | 12 28 04.19 | 12 28 04.20 | 12 28 08.71 |
| δ (J2000.0)..... | 12 33 35.1 | 12 33 06.5 | 12 32 27.2 | 12 34 25.7 |
| F606W (Vega system)..... | 22.86 \pm 0.01 | 22.07 \pm 0.01 | 24.59 \pm 0.02 | 23.65 \pm 0.01 |
| F814W (Vega system)..... | 21.92 \pm 0.01 | 21.14 \pm 0.01 | 23.79 \pm 0.02 | 22.83 \pm 0.01 |
| F606W – F814W..... | 0.94 | 0.93 | 0.80 | 0.82 |
| V (transformed)..... | 23.11 | 22.32 | 24.79 | 23.86 |
| $V - I$ (transformed)..... | 1.20 | 1.19 | 1.01 | 1.04 |
| $V - I$ (dereddened)..... | 1.16 | 1.14 | 0.97 | 1.00 |
| Ellipticity (b/a) ^a | 0.95 \pm 0.04 | 0.88 \pm 0.04 | 0.89 \pm 0.04 | 0.93 \pm 0.04 |
| Estimated luminosity ($10^5 L_{\odot}$)..... | 2.0 | 4.1 | 0.4 | 1.0 |
| Estimated mass ($10^5 M_{\odot}$)..... | 3.1 | 6.5 | 0.7 | 1.6 |
| Half-light radius ($1'' = 80$ pc) (arcsec)..... | 0.025 \pm 0.007 | 0.043 \pm 0.005 | 0.12: | 0.10 \pm 0.01 |
| King profile core radius (arcsec)..... | 0.002 \pm 0.001 | 0.005 \pm 0.001 | 0.031 \pm 0.012 | 0.037 \pm 0.005 |
| King profile tidal radius (arcsec)..... | 1.4 \pm 0.2 | 1.5 \pm 0.1 | 1.7: | 1.0 \pm 0.2 |
| King profile χ^2/ν | 25.6/17 | 26.3/18 | 0.96/10 | 2.47/15 |
| $r^{1/4}$ profile χ^2/ν | 26.8/18 | 35.9/19 | 3.22/11 | 38.5/16 |
| Exponential profile χ^2/ν | 226/18 | 676/19 | 13.5/11 | 71.9/16 |

NOTE.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

^a Ellipticities were measured with the PyRAF task `imexamine`. Errors were calculated as $1 - (b/a)$ for isolated stars in the image.

constrain both the epoch of cluster formation and the system's dynamical history.

Unfortunately, collecting and measuring a large sample of intracluster globular clusters is difficult. Globular clusters in the halos of galaxies are routinely identified as an excess of point sources above the background, and searches for such objects have been conducted in ~ 100 systems out to ~ 100 Mpc (e.g., Harris & Racine 1979; Kissler-Patig 1997; Kundu & Whitmore 2002). However, as galactocentric distances increase, the surface densities of clusters decrease, so in intracluster space, the identification of globular clusters as point sources is exceedingly difficult. As a result, there have been only a few, mostly indirect, studies of IGCs (West et al. 2003; Jordán et al. 2003; Marín-Franch & Aparicio 2003; Bassino et al. 2003), and their use as cosmological probes has largely been unexploited.

Here we describe the results of a *Hubble Space Telescope* (*HST*) search for IGCs in the nearby Virgo Cluster. At our adopted Virgo distance (16.2 Mpc; see discussion in Williams et al. 2007), globular clusters have half-light radii of $\gtrsim 0.05''$, allowing them to be resolved on images taken with the Advanced Camera for Surveys (ACS). Moreover, because of the ACS's excellent sensitivity, it is possible to use the instrument to detect individual stars within the clusters and estimate their metallicities via the color of the red giant branch (RGB). In § 2, we describe our survey and announce the discovery of four well-resolved IGC candidates in Virgo. In § 3, we discuss the metallicities of these objects and show that all are metal-poor, with photometric properties that differentiate them from the globular clusters of Virgo's central cD galaxy, M87. In § 4, we compare the candidate IGCs to Galactic globular clusters and show that their half-light and tidal radii are larger than their Milky Way counterparts. We attribute these properties to the IGCs' lack of tidal processing and use the radii to constrain the clusters' origins. We conclude by estimating the specific frequency of globular clusters in Virgo's intracluster space and discussing the implications that this number has for the origin of IGCs and future IGC surveys.

2. OBSERVATIONS AND REDUCTIONS

Between 2005 May 30 and 2005 June 7, we used the Advanced Camera for Surveys on the *Hubble Space Telescope* to obtain deep

F606W and F814W images of a single Virgo intracluster field [α (J2000.0) = $12^{\text{h}}28^{\text{m}}10.80^{\text{s}}$, δ (J2000.0) = $12^{\circ}33'20.0''$, orientation 112.58°], $\sim 0.67^{\circ}$ (~ 200 kpc) from any large galaxy. The F814W (I band) data consisted of 22 exposures totaling 26,880 s of integration time; the F606W (wide V band) observations included 52 exposures totaling 63,440 s. These data were co-added using the `multidrizzle` task within PyRAF (Koekemoer et al. 2002): this procedure removed all the cosmic rays, corrected the instrument's geometric distortions, and improved the sampling of our data to $0.03''$ pixel $^{-1}$. The details of these reductions, and an image of the field that illustrates its position in the cluster, are given by Williams et al. (2007).

After combining the data, we used SExtractor (Bertin & Arnouts 1996) to identify all sources (extended and unresolved) brighter than $m_{\text{F814W}} = 24.5$, near the peak of the globular cluster luminosity function in Virgo ($V = 23.7$; Whitmore et al. 1995). We then cross-correlated this list with the point-source identifications from DAOPHOT II (Stetson et al. 1990) and searched for objects surrounded by a statistical excess of stars ($N \geq 4$). This procedure yielded eight sources, three of which were obvious background galaxies with internal structure and one of which was clearly surrounded by misidentified background galaxies. However, the remaining four objects had the properties expected for IGCs. Each was well resolved and roughly spherical ($b/a \geq 0.88$), each had an integrated F814W magnitude near the peak of the Virgo globular cluster luminosity function, and each was surrounded by point sources that had the colors and magnitudes of Virgo Cluster red giant stars. The coordinates of these four sources, aligned to the astrometry of the automatic plate measuring (APM) machine catalog,¹ are given in Table 1; images of the objects are displayed in Figure 1.

We performed photometry on the point sources surrounding the IGC candidates using DAOPHOT II (Stetson et al. 1990). Instrumental magnitudes in $0.5''$ apertures were computed via point-spread function (PSF) fitting. These magnitudes were then extrapolated to infinite apertures and placed on the Vega magnitude system using the correction parameters and photometric zero

¹ See <http://www.ast.cam.ac.uk/~apmcat>.

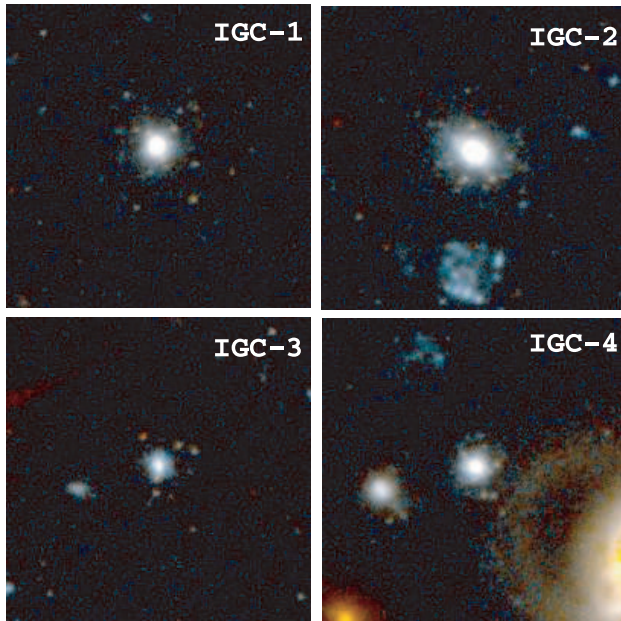


FIG. 1.—Color images of our four IGC candidates produced by combining our F606W and F814W exposures. Each image is $6'' \times 6''$ on a side, with north up and east to the left. Note the number of point sources surrounding each candidate; these are likely to be red giant stars in the outer regions of the clusters. Also note the well-resolved background galaxies, for example, south of IGC-2 and east of IGC-3 and IGC-4. These objects are much more extended than the stars or IGC candidates.

points given by Sirianni et al. (2005). Photometry of the candidate IGCs themselves was performed with the IRAF² task *phot*, using a series of concentric circular apertures ranging in size from $0.0225''$ to $1.35''$. Within $0.25''$, these aperture radii were incremented in $0.0225''$ intervals; outside this radius, aperture widths were increased to maintain a near-constant photometric error. Again, these instrumental magnitudes were converted to the Vega magnitude system using the zero points of Sirianni et al. (2005). Transformations to the standard *VI* magnitude system were performed using the coefficients of Rejkuba et al. (2005). We note, however, that these transformations have a rather large scatter, ~ 0.05 mag. Consequently, this last step was only used to compare the integrated magnitudes of our globular cluster candidates with other measurements in the literature. Whenever possible, we confined our analysis to the F606W – F814W magnitude system.

To translate our photometric measurements into physical parameters, we first dereddened the observed magnitudes using the Schlegel et al. (1998) value for Galactic foreground extinction [$E(B - V) = 0.025$]. With the reddening law of Cardelli et al. (1989) and the ACS filter transformations of Sirianni et al. (2005), this corresponds to $A_V = 0.077$, $A_I = 0.046$, $A_{F606W} = 0.069$, and $A_{F814W} = 0.045$. Total luminosities for the IGC candidates were then calculated assuming a Virgo distance of 16.2 Mpc and a bolometric correction of $BC_V \approx -0.5$ (with $M_{\text{bol}\odot} = 4.74$). Finally, these luminosities were used to estimate masses by assuming a mass-to-light ratio of $M/L_V = 2.3$, which is typical for Galactic clusters (Pryor & Meylan 1993).

To test whether our candidate IGCs are true globular clusters, we convolved a series of King (1962) model profiles with a

Moffat (1969) representation of the F814W filter point-spread function and fitted the resulting curve to the objects' radial profiles using a χ^2 minimization procedure. The best fits are shown in Figure 2, with the photometric errors increased by 5% (added in quadrature) to account both for deviations between the true PSF and our Moffat function, and for the “red halo effect” (Sirianni et al. 2005). The best-fit core radii, tidal radii, and half-light radii are given in Table 1; the errors on these numbers are the standard deviations of fits to a series of Monte Carlo simulations of each brightness profile. (The data for IGC-3 [our faintest candidate] were not of sufficient precision to constrain the tidal radius, so no errors are given for this object.) In all four cases, our convolved King profiles provide good fits to the data, with $\chi^2/\nu \leq 1.5$. This contrasts with fits that use the de Vaucouleurs (1959) $r^{1/4}$ law or an exponential disk (also given in Table 1), which generally give poorer χ^2 values. The quality of the fits strongly supports the conclusion that these objects are indeed globular clusters.

Additional support for the globular cluster interpretation comes from the point sources surrounding each IGC candidate. The mean density of all unresolved sources detected in our intracluster survey field (down to a limiting magnitude of $m_{F814W} = 28.5$) is 480 arcmin^{-2} (Williams et al. 2007). Thus, we would expect ~ 0.67 stars to be projected between $0.3''$ and $1.3''$ from the center of each IGC candidate. Even the faintest of our candidates has 6 times this number; the Poisson probability of having four or more stars randomly projected about a $m_{F814W} < 24.5$ object in our field is less than 0.5%. Since there are 195 such objects present in the region, at most one of our IGC candidates is expected to be a chance superposition of stars around a bright unrelated object, and a visual examination of the candidates reduces this number further.

The final piece of evidence supporting the IGC identification is the magnitude of the brightest stars surrounding each cluster, $I \sim 27$. This is the magnitude expected of red giant stars at the distance of Virgo (Ferguson et al. 1998; Durrell et al. 2002). It therefore seems likely that the sources surrounding each IGC candidate are red giants bound to the clusters.

Can the objects be background galaxies or some other sources unrelated to globular clusters? The radial profile of IGC-1 can be fitted with both a King model and an $r^{1/4}$ law ($\chi^2/\nu = 1.5$), so it is conceivable that this object is a field elliptical galaxy. However, IGC-1 is also bright enough to have photometry from the Sloan Digital Sky Survey (Adelman-McCarthy et al. 2006), and its Sloan $u' - g'$ and $r' - i'$ colors (0.3 ± 0.7 and 0.0 ± 0.4 , respectively) are bluer than those of any normal elliptical galaxy at any redshift (Csabai et al. 2003). This fact, along with the object's $g' - i'$ and $V - I$ colors, which are bluer than those of local small elliptical galaxies (Csabai et al. 2003; Fukugita et al. 1995) but similar to those of Virgo globular clusters (e.g., Forbes et al. 2004; Kundu et al. 1999), makes it extremely unlikely that the object is a background galaxy. Similarly, although the radial profile of our faintest candidate, IGC-3, can be fitted with an $r^{1/4}$ law (with $\chi^2/\nu = 0.3$), King models or a Sersic (1968) profile with $n = 0.5$ (i.e., an isothermal distribution) generate an even lower value of χ^2 , and the object's $V - I$ color is again much bluer than that expected from a normal elliptical galaxy. Finally, IGC-2 and IGC-3 are our most elongated IGC candidates (see Table 1), with shapes that are more eccentric than $\sim 80\%$ of Galactic globular clusters (Harris 1996). While it is possible that the more elliptical Galactic clusters are tidally disturbed by the Galaxy, it is clear that these ellipticities do not rule out a globular cluster classification. In any case, King profiles provide much better fits to these candidates than any exponential or $r^{1/4}$ law.

² IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

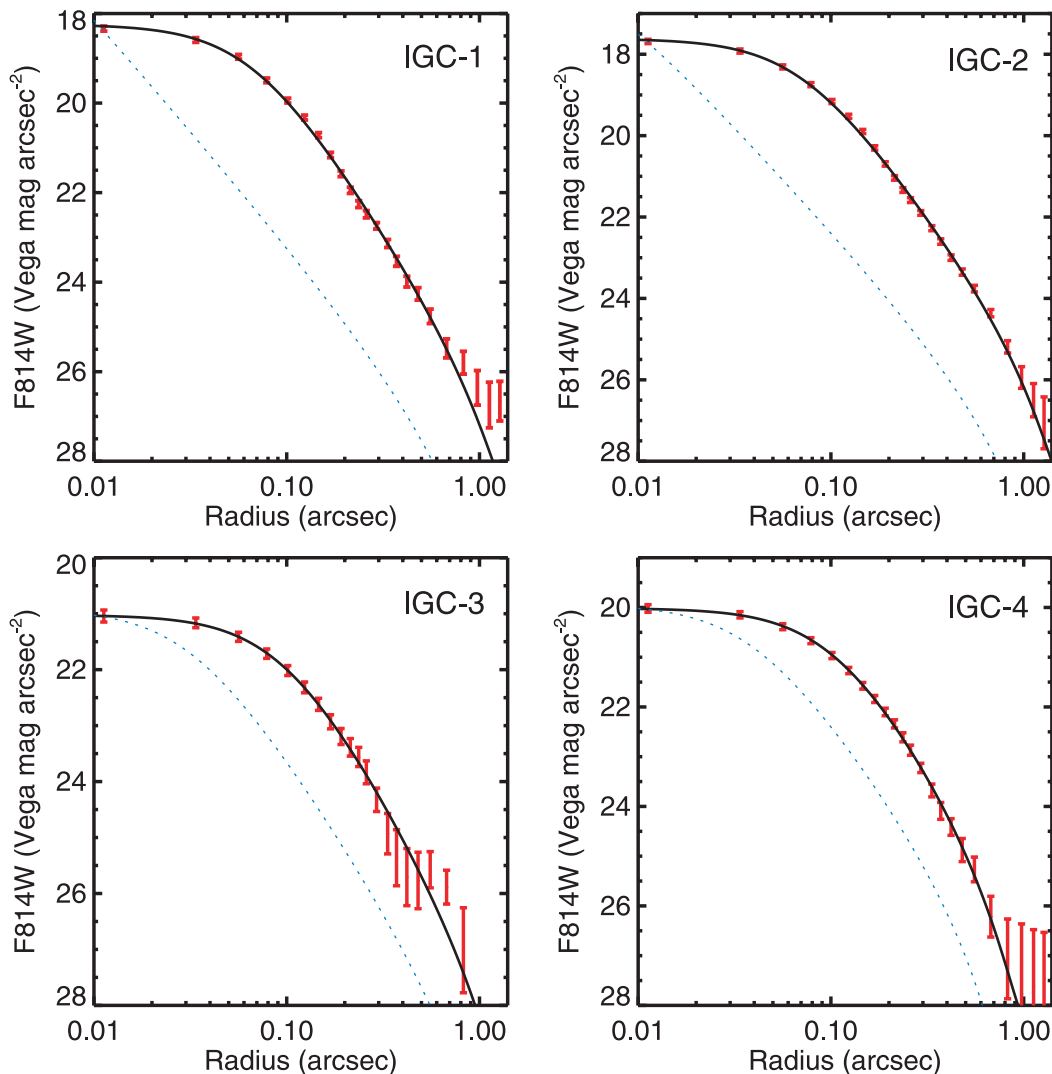


FIG. 2.—Azimuthally averaged radial surface brightness profiles of our four IGC candidates in the F814W filter. The black solid curves show the best-fitting King (1962) profiles convolved with a Moffat (1969) approximation of the ACS point-spread function. The unconvolved King profile is illustrated by the blue dotted line in each panel. Fitting statistics and parameters are given in Table 1. Note the excellent quality of the fits; profiles based on de Vaucouleurs (1959) profiles or exponential laws are not nearly as good.

In fact, the only objects that could reproduce the observed properties of our IGC candidates are the nuclear remains of tidally stripped dwarf galaxies. Such an origin has been proposed for the Milky Way object ω Cen (e.g., Bekki & Freeman 2003; Mackey & van den Bergh 2005), the giant globular cluster G1 in M31 (Meylan et al. 2001), the most massive clusters of NGC 5128 (Martini & Ho 2004), and the ultracompact dwarf galaxies of Virgo and Fornax (Drinkwater et al. 2000, 2004; Jones et al. 2006). However, all of our IGC candidates are much fainter than these unusual objects; for example, ω Cen is over a magnitude brighter than our most luminous IGC candidate, and the ultracompact dwarf galaxies found by Drinkwater et al. (2000) and Jones et al. (2006) are brighter still. Of course, it is difficult to completely exclude the possibility that our IGCs are stripped dwarf galaxies; ω Cen is more than 1000 times closer than Virgo, and its classification is still controversial (van Leeuwen et al. 2002). Nevertheless, given that all four candidates have luminosities near the peak of the globular cluster luminosity function, the simplest explanation for these sources is that they are indeed normal globular clusters at the distance of Virgo.

3. THE METALLICITIES OF THE IGCs

Figure 3 plots the point sources within $1.3''$ (~ 100 pc at Virgo) of each globular cluster candidate on a F606W – F814W color-magnitude diagram (CMD). Overplotted are isochrones for an old (12.5 Gyr) stellar population (Girardi et al. 2002; L. Girardi 2006, private communication) at the distance of Virgo. These sparse CMDs suggest that all four of our IGC candidates are metal-poor. The most metal-rich of the group, IGC-4, has $[M/H] \sim -1.3$, while the stars of IGC-2 and IGC-3 fall close to the most metal-poor isochrone ($[M/H] \sim -2.3$). Curiously, four of the point sources surrounding IGC-1 fall bluerward of any of the L. Girardi (2006, private communication) isochrones, in a region of the H-R diagram occupied primarily by background sources (Williams et al. 2007). It is possible that either there is an overdensity of background objects in this part of the field or that the effects of crowding have produced errors in the stellar photometry that are larger than the standard errors shown on the CMD. In any case, if we exclude these objects from the analysis, the remaining stars of the cluster imply a metallicity of $[M/H] \sim -1.5$.

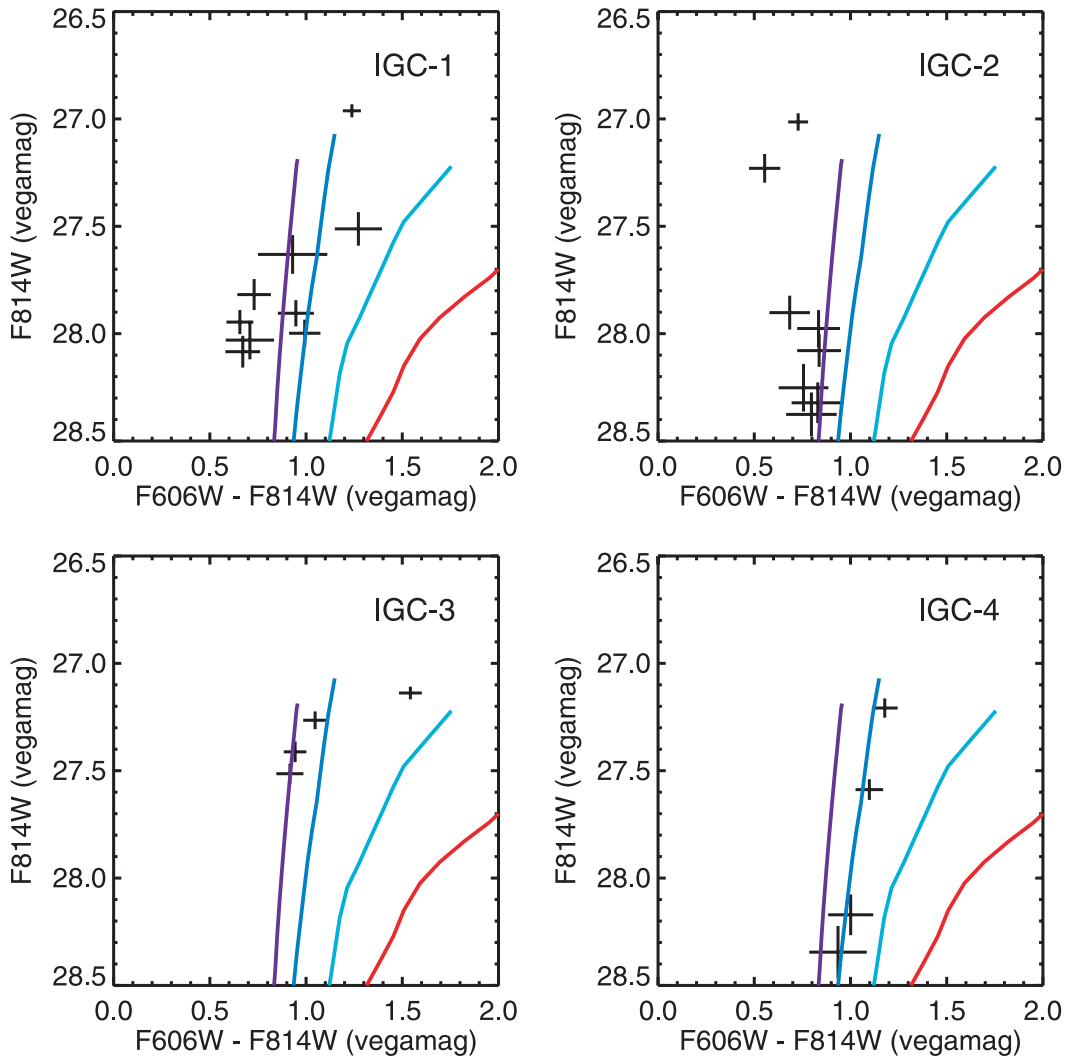


FIG. 3.—Color-magnitude diagrams of the point sources projected within $1.3''$ of each IGC candidate. Overplotted are theoretical 12.5 Gyr isochrones for stellar populations with $Z = 0.008$ ($[M/H] = -0.4$; red), $Z = 0.004$ ($[M/H] = -0.7$; cyan), $Z = 0.001$ ($[M/H] = -1.3$; blue), and $Z = 0.0001$ ($[M/H] = -2.3$; purple). On average, only ~ 0.67 stars in each panel should be a chance superposition. Note that all four systems are metal-poor: IGC-4, the most metal-rich of the group, has $[M/H] \sim -1.3$.

The metal-poor nature of our globular cluster candidates is supported by their integrated colors, although not to the extent that one might expect. In most large galaxies, the distribution of globular cluster colors is bimodal (e.g., Gebhardt & Kissler-Patig 1999; Larsen et al. 2001; Kundu & Whitmore 2001; Harris et al. 2006). For example, the color distribution of M87 globular clusters is well modeled by two Gaussians, one with a peak at $V - I = 0.95$ and the other centered at $V - I = 1.20$ (Whitmore et al. 1995; Kundu et al. 1999). This division has generally been interpreted as evidence for the existence of two separate populations of clusters, one consisting of blue, “metal-poor” objects, and the other comprised of “metal-rich” systems (Harris et al. 2006; but see Yoon et al. 2006 for an alternative explanation). The integrated colors of clusters IGC-3 and IGC-4 clearly place them in the metal-poor category, as one might expect from the colors of their halo stars. However, IGC-1 and IGC-2 both have colors that fall slightly to the red of the dividing line. This seems incompatible with the colors of the systems’ red giant stars.

To investigate this inconsistency, we measured the objects’ radial color profiles. As Figure 4 demonstrates, IGC-1 and IGC-2 both have significant color gradients, with the clusters’ interiors being redder than their halos by ~ 0.2 mag. Such gradients are

usually associated with galaxies, and, as mentioned above, it is conceivable that these two clusters are actually the stripped remains of compact dwarf galaxies (Drinkwater et al. 2004; Jones et al. 2006). But this need not be the case: in the Galaxy, one-third of all globular clusters have similar red-to-blue gradients (Chun & Freeman 1979; Sohn et al. 1998). Whether these gradients are caused by the effects of mass segregation, the random presence of a few relatively bright stars (Peterson 1986), or chemical inhomogeneities in the stellar populations (Freeman 1980) is unclear. However, it does explain how our two IGC candidates can have neutral colors but still exhibit metal-poor CMDs. It is therefore possible that these two IGCs are of intermediate metallicity. Future spectroscopy can provide a definitive answer to this question.

The fact that all four of our IGC candidates are relatively blue stands in marked contrast to the color distribution of clusters in M87’s inner regions. M87’s globular clusters have a mean value of $V - I = 1.10$, and $\sim 60\%$ are classified as “metal-rich” on the basis of their red colors. All of our IGC candidates have metal-poor RGBs, and our two reddest clusters just barely fall on the red side of the color distribution. To a limited extent, this is consistent with the results of Harris et al. (2006), who showed that outside of ~ 5 kpc, the ratio of red to blue clusters surrounding the brightest

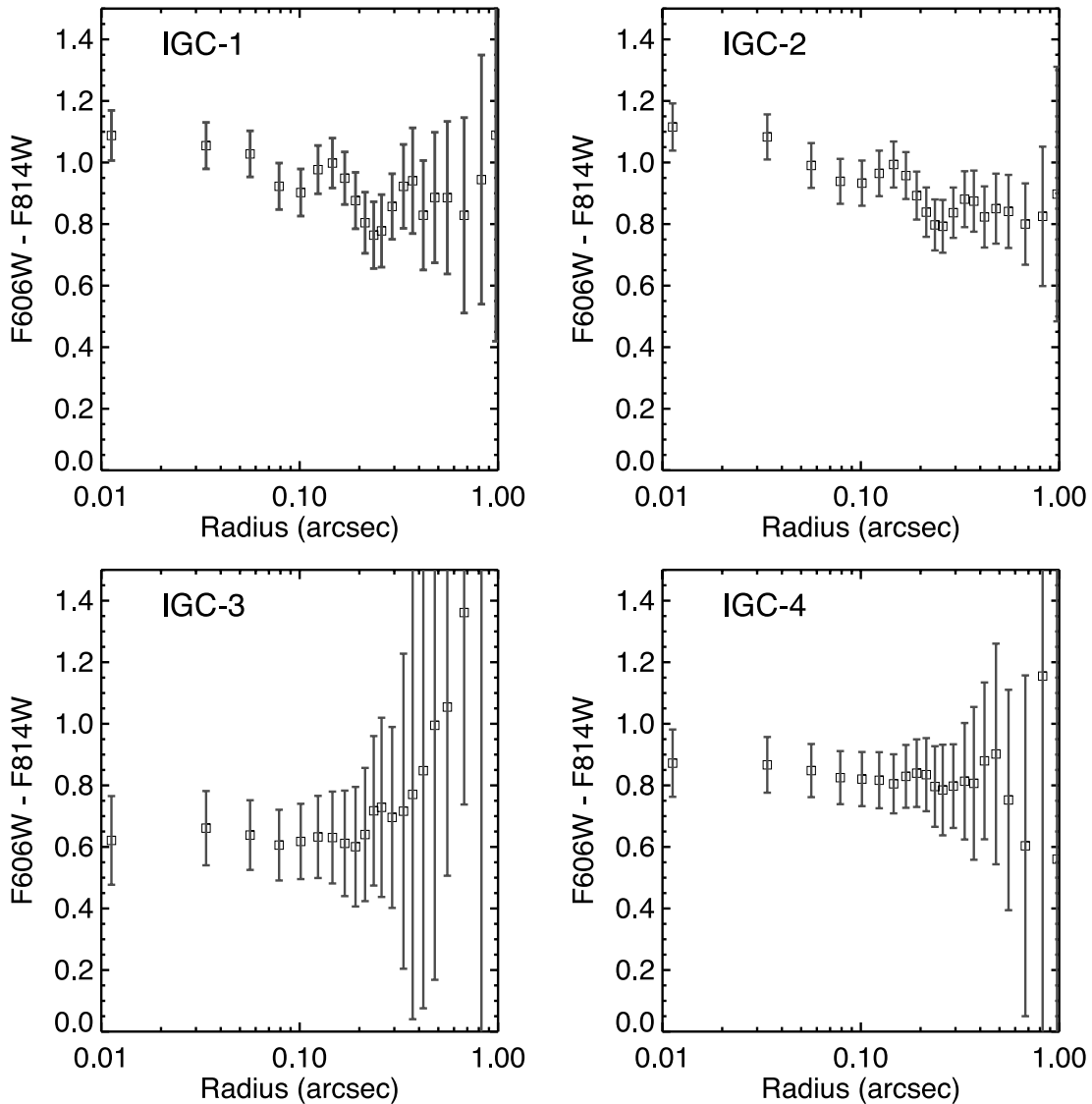


FIG. 4.—The $F606W - F814W$ colors of our globular cluster candidates, computed in a series of circular annuli. Note the color gradients associated with IGC-1 and IGC-2; roughly one-third of Galactic clusters have such gradients. This partially explains why these metal-poor systems have integrated colors that are slightly redder than the mean for the M87 globular clusters. [See the electronic edition of the *Journal* for a color version of this figure.]

cluster galaxies drops dramatically. However, in the Harris et al. (2006) sample, the fraction of red clusters never drops below $\sim 40\%$, even at galactocentric distances of ~ 30 kpc. The IGCs in our intracluster field are ~ 200 kpc from any galaxy, and the probability of observing four clusters with $V - I \lesssim 1.16$ out of the Harris et al. (2006) distribution is just $\sim 10\%$. These numbers suggest that the IGC population in our field is fundamentally different from that associated with the brightest cluster galaxies.

Alternatively, it is possible that the four globular cluster candidates observed in our small intracluster field are not representative of the Virgo IGC population as a whole. Three of the four clusters, IGC-1, IGC-2, and IGC-3, are located in a line that runs north-south along the western half of our field. Since these clusters are also the most metal-poor of our candidates, it is possible that all three originated in a single stripped galaxy and that the stream has not yet completely mixed with the general intracluster population. Indeed, the spatial substructure exhibited by the metal-poor stars in our ACS field is evidence for just such a scenario (Williams et al. 2007). If coherent streams are com-

mon, then a much wider survey will be needed to reliably measure the properties of Virgo's globular clusters.

4. THE IGC RADIAL PROFILES

Figure 5 compares the core and tidal radii of our objects IGC-1, IGC-2, and IGC-4 with those of Galactic globular clusters, using our adopted Virgo distance. (IGC-3 is not plotted, since its tidal radius is unconstrained.) From the figure, we can see that, although the core radii of the two sets of objects are comparable, the tidal radii of the intergalactic objects are larger than most of their Milky Way counterparts. This is not a selection effect; since our IGC search criteria included all sources detected by SExtractor, our sample is not biased by size. In fact, a close examination of Figure 5 shows that the tidal radii of our IGC candidates are similar to those of the Milky Way clusters with large Galactocentric distances. This agrees with the thesis that globular clusters inside large galaxies are continually affected by tidal stress.

Such stress is thought to play a key role in the evolution of galaxy-bound clusters. For example, analyses by Aguilar et al. (1988) and Fall & Zhang (2001) suggest that over a Hubble

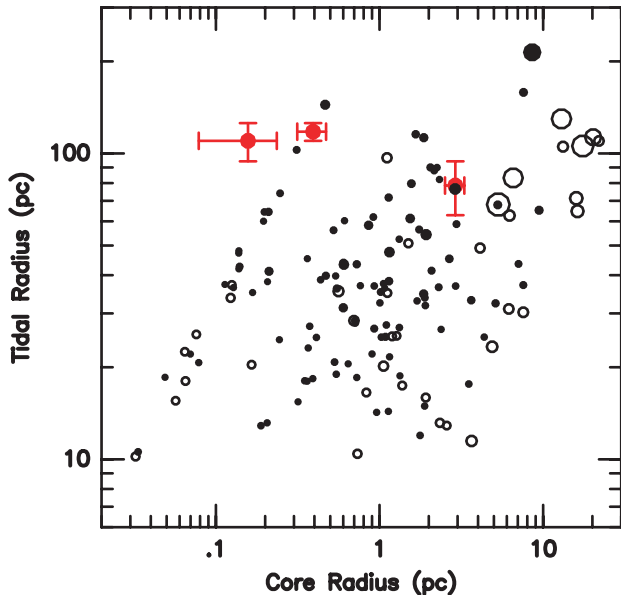


FIG. 5.—Core radii and tidal radii of our IGC candidates (*large red circles*), excluding IGC-3, whose tidal radius is unconstrained. For comparison, the parameters of Galactic globular clusters are also plotted. The filled circles represent clusters brighter than $M_V = -6.5$, which is the magnitude limit of our observations. The open circles represent fainter clusters. The sizes of the circles are proportional to their Galactocentric distances (from 0.6 to 120 kpc). Note that the intergalactic globular clusters have systematically larger tidal radii than their Galactic counterparts, and that many of the Galactic objects with large tidal radii are at large Galactocentric distances. This is consistent with the idea that our IGC candidates have evolved in a largely stress-free environment.

time, a large fraction of globular clusters within a Milky Way–type spiral galaxy will be either stripped or destroyed. However, if our IGCs were created in situ, or if their parent galaxies were low-mass objects, then tides have never been important for their dynamical evolution. Support for this idea also comes from the observations of Jordán et al. (2005), who showed that in the Virgo Cluster the half-light radii of globular clusters systematically increases with galactocentric distance.

The large tidal radii of the clusters provide a hint about the length of time for which the IGCs have been free-floating. Dynamical models predict that globular clusters recover from galactic tidal shocking on a half-mass relaxation timescale, which is typically $(5\text{--}10) \times 10^8$ yr (Johnston et al. 1999). After several of these relaxation times, the clusters will lose any structures caused by past tidal effects and approach a distribution governed by the gradient of the galaxy cluster’s potential, a value that is $\sim 10^{-3}$ times smaller. The fact that the IGCs are well fitted by King profiles with finite tidal radii suggests our objects were once affected by the tidal field of a galaxy (Heggie 2001), but are now internally evolving toward a state with little tidal truncation. Since this process can take 5–10 Gyr (Johnston et al. 1999), the observations imply that these IGCs have been free-floating, unaffected by strong tidal influences, for several Gyr.

5. ORIGINS OF THE CLUSTERS

In order to place these IGC candidates into a context of galaxy cluster evolution, it is important to compare our surface density results with previous surveys for these objects. The existence of four IGCs within our 11.4 arcmin² field implies that Virgo’s IGC surface density is $\sim 10^{-4}$ arcsec⁻². If we scale this number to the distance of Coma (a distance ratio of 6; Dressler 1984), then our data imply a surface density that is safely below the upper limit of

0.004 arcsec⁻² measured by Marin-Franch & Aparicio (2003). In contrast, a scaling of our surface density to the distance of A1185 ($cz = 9800$ km s⁻¹) yields a value that is a factor of 2 larger than that observed by Jordán et al. (2003). However, since their survey only reached one magnitude *brighter* than the peak of the globular cluster luminosity function, while our observations go 0.8 mag *fainter* than the peak, the two values are compatible.

The number of IGCs places an interesting constraint on the specific frequency (S_N) of globular clusters in Virgo’s intracluster environment. Star counts (after the statistical removal of unresolved background galaxies) in our 11.4 arcmin² field reveal ~ 5300 stars brighter than $m_{F814W} \sim 29$ (Williams et al. 2007). If we extrapolate these counts down to the main sequence using the isochrones of L. Girardi (2006, private communication), then the data imply an intracluster surface brightness of $\mu_V \sim 28.1$ mag arcsec⁻² (for details, see Williams et al. 2007), an absolute total luminosity of $\sim 2 \times 10^5 L_\odot$ kpc⁻², and a globular cluster specific frequency of $S_N \sim 6$. This relatively high value suggests that we have not missed a significant number of IGCs and that the properties of these four IGCs may be representative of the IGC population in Virgo.

Our value of $S_N \sim 6$ can be used to place a constraint on the origins of the Virgo intracluster population. If most of the stars in Virgo’s intergalactic space originated in typical spiral galaxies (i.e., were liberated via the galaxy harassment scenario of Moore et al. 1996, 1999), then we would expect to measure a much lower value for the globular cluster specific frequency, with $S_N \sim 1$ (e.g., Goudfrooij et al. 2003; Chandar et al. 2004). This argument may apply to low surface brightness spiral galaxies as well (J. H. Kim et al. 2007, in preparation). Alternatively, if intracluster stars are the disrupted remains of low-luminosity dwarf galaxies, then the value of S_N should be ~ 20 (Grebel et al. 2000; Strader et al. 2003). Our value for the specific frequency of globular clusters lies between these two extremes, in the range normally associated with cD galaxies (West et al. 1995; Forbes et al. 1997) and dwarf elliptical galaxies (Durrell et al. 1996; Miller et al. 1998; Beasley et al. 2006). In fact, dwarf elliptical galaxies are the most common morphological type in galaxy clusters (Binggeli et al. 1988), and the Virgo core currently contains about 900 of these objects. This is a significant number of galaxies: Durrell et al. (2002) estimate that if two-thirds of all dwarf elliptical galaxies are destroyed through gravitational interactions over a Hubble time, then their remnants could account for Virgo’s entire intracluster population.

The preceding has two caveats. First, the low metallicities and high specific frequency of IGCs could be due to preferential stripping of globular clusters during tidal encounters. The radial distribution of clusters within a galaxy is often flatter than that of the galaxy’s light (e.g., Puzia et al. 2004; Forbes et al. 2006); this fact is consistent with the idea that such systems are often formed during galactic mergers and interactions (Ashman & Zepf 1992). Since clusters (and stars) in the outskirts of galaxies are more susceptible to tidal forces than interior objects, this mismatch can lead to the increased stripping of globular clusters with respect to the stars. The result is that in rich clusters, where tidal encounters are important, the specific frequency of clusters in intergalactic space can be enhanced at the expense of galactic values. There is some evidence for just this effect: in Virgo, some galaxies have lower values of S_N than their field counterparts (see Elmegreen 1999 and references therein). Moreover, since systems of blue globular clusters often have flatter radial distributions than those of red clusters (e.g., Bassino et al. 2006; Forbes et al. 2006; Harris et al. 2006), this process can explain why the four IGC candidates found in our survey are all metal-poor.

A second caveat to our measurement of S_N concerns the survival of clusters in the galactic and extragalactic environments. In large galaxies, bulge shocks, disk shocks, and dynamical friction all take their toll on the globular cluster population, so that, over a Hubble time, a large fraction of clusters will be destroyed (Aguilar et al. 1988). Such processes do not occur in intergalactic space. Consequently, while values of S_N in a passively evolving galaxy can decline with time, the specific frequency of IGCs can actually increase (this is because the IGCs are not destroyed and the luminosity of the normalizing intracluster stellar population decreases as it ages). The importance of this effect is difficult to model, since it depends critically on where and when the IGCs originally formed. However, like the effects of preferential stripping, this mechanism will produce higher values of S_N for the intracluster environment than for the clusters' parent galaxies.

The metallicities of our IGC candidates alone do not help determine the clusters' origins, as most globular cluster systems contain a significant blue (metal-poor) component. However, the relatively blue colors and metal-poor CMDs of our candidates do support the hypothesis of Harris et al. (2006) that redder, more metal-rich clusters must form later in the deeper potential wells of major galaxies. The fact that none of our IGCs are metal-rich implies that, once they are formed, it is difficult to eject red clusters into intergalactic space.

6. FUTURE POSSIBILITIES

In order to properly investigate the systematics of IGCs, one needs a much larger sample of objects. The key to obtaining such a sample is spatial resolution: with ground-based images,

it is extremely difficult to distinguish IGCs from the (much more numerous) background contaminants. However, the fact that four IGCs were discovered in a single ACS field suggests that with a few additional *HST* pointings, one can identify an astrophysically interesting sample of such objects. With *HST* resolution, one can obtain the IGCs' structural parameters, measure their tidal radii, and investigate the systematics of a set of clusters that have evolved in a largely stress-free environment. Moreover, with follow-up ground-based spectroscopy one can measure conclusive ages and metallicities.

Such a sample can be a powerful probe of galactic and cluster evolution. By comparing the luminosities of globular clusters in and outside of galaxies, one can test for the effects that bulge and disk shocking have on the globular cluster luminosity function. Similarly, by examining the distribution of tidal radii for IGCs, one can probe the length of time that these objects have been in the intergalactic environment and complement population constraints imposed by the intracluster stars. Finally, with a large sample of clusters, we can test whether the bimodal color and metallicity distributions often seen around large galaxies extend to the intracluster population and whether "red" clusters can be liberated from their parent galaxies. Such tests, in turn, can place new constraints on the formation of these objects.

Support for this work was provided by NASA through grant GO-10131 from the Space Telescope Science Institute and by NASA through grant NAG5-9377.

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