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# THE DISCOVERY OF REMOTE GLOBULAR CLUSTERS IN M33

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## ABSTRACT

We present the discovery of four remote star clusters in M33, one of which is of an extended nature. Three of the clusters were discovered using survey data from the Isaac Newton Telescope Wide-Field Camera while one was discovered serendipitously in a deep image taken with the *Hubble Space Telescope*'s Advanced Camera for Surveys. With projected radii of 38–113 arcmin (9.6–28.5 kpc for an assumed M33 distance of 870 kpc), these clusters lie significantly beyond all but one of the currently confirmed clusters in M33. The clusters have magnitudes and colors consistent with their being old to intermediate-age globular clusters (GCs). Indeed, they bear a strong resemblance to the outer halo GC population of the Milky Way and M31 in terms $(V - I)_0$ color. The three outermost clusters are projected on the far side of M33 with respect to M31, an asymmetry that could suggest tidal interactions have affected M33's GC distribution at large radii.

*Key words:* galaxies: evolution – galaxies: formation – galaxies: individual (M33) – galaxies: star clusters – galaxies: stellar content

## 1. INTRODUCTION

Globular clusters (GCs) have proved to be valuable probes of galaxy formation, providing key clues about the assembly histories of the Milky Way (hereafter MW; e.g., Searle & Zinn 1978), and M31 (e.g., Perrett et al. 2002). A particular property of GCs that makes them especially important is that they can often be found out to extremely large radii in galaxy halos. Such outer halo GCs are key tracers of the baryonic content and dynamics of galaxies on scales of tens to hundreds of kiloparsecs (e.g., Evans & Wilkinson 2000).

First discovered by Madore & Arp (1979), AM-1 remains the most distant GC known in the MW with a galactocentric distance of 123 kpc. M31 hosts GCs at much larger radial distances, out to $\gtrsim$200 kpc, however, this population has only been uncovered in the last few years thanks to sensitive panoramic digital imaging surveys (e.g., Martin et al. 2006; Huxor et al. 2008). For example, using 84 deg$^2$ of imaging data from the Isaac Newton Telescope Wide-Field Camera (INT/WFC) and Canada–France–Hawaii Telescope (CFHT) MegaCam surveys of M31, Huxor et al. (2008) were able to increase the number of known GCs with projected radii $\gtrsim$ 1 deg ($\approx$14 kpc at M31's distance) by more than 75%; this is especially remarkable given that most of this data came from a single outer quadrant of M31 and suggests that many more halo GCs remain to be discovered in that system.

M33 is the least massive spiral in the Local Group and there has been much interest in understanding how its star cluster system compares to that of its larger brethren. Previous studies have suggested that, like the MW and M31, M33 has a population of star clusters which exhibit halo kinematics but that these clusters possess a much larger age spread and a higher mean metallicity than their MW counterparts (e.g., Sarajedini et al. 2000; Chandar et al. 2002). Indeed, M33 appears to have a cluster population with a very broad range of ages, bearing a stronger resemblance to the cluster populations of the lower mass magellanic Clouds rather than the MW or M31.

One drawback of all M33 star cluster studies to date is that they have focused only on objects projected on the inner regions of the galaxy, with little exploration of the galaxy outskirts. This bias has made it rather difficult to unambiguously associate clusters with the disk or the halo. The Chandar et al. (2002) study, for example, includes only objects that lie within a projected radius of 5 kpc, corresponding to just over half the isophotal $R_{25}$ radius of 9 kpc (de Vaucouleurs et al. 1991). Sarajedini & Mancone (2007, hereafter SM07) have recently compiled a list of all M33 star clusters and cluster candidates identified in all previous studies. This has led to the creation of a unified catalog of ~300 "high-confidence" objects. The most remote cluster reported in the original SM07 catalog lies at a mere 7 kpc in projected radius. Since the publication of SM07, Zloczewski et al. (2008, hereafter ZKH08) have conducted a search for new star clusters in the outskirts of M33 based on 0.75 square degrees of deep CFHT MegaCam imagery. Although their survey has led to the discovery of more than 120 new star cluster candidates, none of these lie beyond a projected galactocentric radius of 8.3 kpc.

In order to establish whether M33, like its larger neighbors, also possesses a population of remote halo star clusters, we have undertaken a search for GCs in INT/WFC survey data of M33, as well as in our own deep *HST* Advanced Camera for Surveys (ACS) imagery of two outer fields in M33. Our search has resulted in the identification of four new outlying star clusters in M33, which lie at projected radii of 10–30 kpc. A fifth cluster was also uncovered in our search but it has since been published by Stonkutė et al. (2008) who independently found the object in Subaru Suprime-Cam data (M33-EC1). Throughout this paper, we adopt a distance modulus to M33 of $(m - M)_0 = 24.69$, corresponding to 870 kpc, for consistency with SM07.

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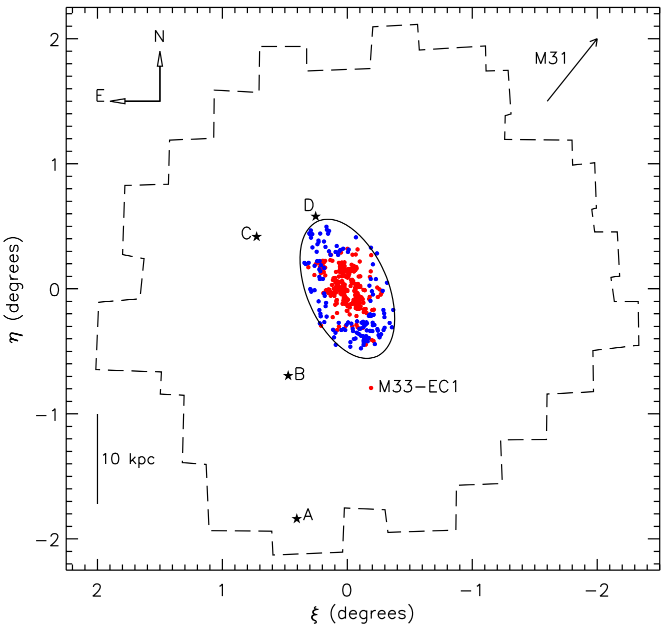


**Figure 1.** Locations of the new clusters (black stars) are shown in relation to the "high-confidence" clusters in the SM07 catalog (red circles) and the "probable clusters" of ZKH08 (blue circles). The Stonkutė et al. (2008) cluster, M33-EC1, is labeled, and an arrow indicates the direction to M31. The solid ellipse indicates the $R_{25}$ isophote and the dashed outline indicates the extent of our INT/WFC survey coverage. The outermost of the new clusters, along with the remote extended cluster of Stonkutė et al. (2008), project on the far side of M33 with respect to M31.

## 2. OBSERVATIONS

The primary data set used in our GC search is the INT/WFC survey of M33 which was conducted over several observing runs in 2002–2008. The WFC is a four-chip CCD mosaic camera with a 0.29 deg$^2$ field of view and a pixel scale of 0.33 arcsec pixel$^{-1}$, equipped to the INT 2.5 m telescope on La Palma. Exposures of 900–1200 s were taken in both the Johnson $V$ and Gunn $i$ bands, with a median seeing of 1$''$.2. This depth is sufficient to detect individual stars in M33 to $V \sim 24.5$ and $i \sim 23.5$ with a typical signal-to-noise ratio (S/N) of 5. The fields observed comprise a contiguous, almost circular, region, covering approximately 12 deg$^2$, very much greater in extent than any previously published survey of M33 (see Figure 1). The survey data were processed using the standard INT Wide Field Survey pipeline provided by the Cambridge Astronomical Survey Unit; as discussed in Irwin & Lewis (2001), this pipeline provides basic data processing and astrometric and photometric calibration, as well as object detection and classification.

Our star cluster search concentrated on only those regions beyond the main optical disk of M31. We adopted a strategy similar to that used in our search for GCs around M31 (Huxor et al. 2008) and which exploits the fact that clusters at the distance of M31 and M33 should be just resolved in good seeing. Indeed, given the survey depth, we expect detection of individual red giants down to ~3 mag below the tip of the red giant branch. Initial GC candidate selection was based on source magnitude, color, and morphological classification (stellar/nonstellar) provided by the photometric pipeline, exploiting the fact that most known GCs lie within specific ranges of absolute magnitude ($-10.5 \lesssim M_V \lesssim -3.5$, equivalent to $14 \lesssim V \lesssim 21$ at the distance of M33) and color ($0 \lesssim V - I \lesssim 1.7$). These generous regions of parameter space are sufficient to allow for photometric errors and avoid exclusion of any slightly atypical GCs from the candidate list generated. Unlike our search for M31 GCs, ellipticity and object FWHM were not employed as search criteria since the number of initial candidates selected using just magnitude, color, and morphology alone was not prohibitively large and all candidates could be visually inspected. As in Huxor et al. (2008), every single survey image was also visually inspected in order to identify well-resolved diffuse extended GCs. Such objects are rather common in the outskirts of M31 (e.g., Huxor et al. 2005, 2008) and would not have been automatically found by the method above as they do not appear as a single source in the object catalog.

We also conducted a search for outlying star clusters in two deep *HST*/ACS pointings that we obtained along M33's northern major axis at radii of 36$'$ and 46$'$. These data were taken in the F606W and F814W filters as part of GO PID 9837 (PI: A. Ferguson) with total exposure times of 18,050 and 12,955 s, respectively, and are being used for an analysis of the star formation history of M33's outer disk (M. K. Barker et al. 2009, in preparation). The star cluster search in this data set was conducted purely by visual inspection of the drizzled stacked frames since star clusters at the distance of M33 are very well-resolved in *HST*/ACS imagery.

## 3. RESULTS

Our search resulted in the identification of four new outlying star clusters in M33, three of which were discovered in the INT/WFC survey data and one in the *HST*/ACS data. It is worth noting that although the *HST*/ACS frames lie within the INT/WFC areal coverage, the *HST* cluster was not independently found in the INT/WFC survey data. This cluster is faint (see below) but, more importantly, rather compact in appearance hence it was not possible to distinguish it as a cluster in our ground-based imaging. Figure 1 shows the locations of these objects with respect to the "high-confidence" clusters from SM07 and the ZHK candidate clusters. Our new discoveries lie at galactocentric radii ranging from 38 to 113 arcmin, which corresponds to 9.6–28.5 kpc for an assumed M33 distance of 870 kpc, and are clearly more remote than all but one of the known population. If these clusters are associated with M33's disk rather than halo, then their deprojected radii would be even more extreme, corresponding to 10–38 kpc.

Figure 2 shows images of the four newly discovered clusters. Two of these clusters (HM33-B and HM33-C) are high surface brightness and compact while one cluster (HM33-A) is diffuse and extended, much like M33-EC1 reported by Stonkutė et al. (2008). Figure 2 also shows the stacked F606W image of the cluster (HM33-D)[7] discovered in the *HST*/ACS image.

Integrated photometry of the new INT/WFC clusters was undertaken with the IRAF task *apphot*.[8] Fluxes within an aperture of radius 8$''$ were obtained for clusters HM33-B and HM33-C; this aperture was selected to allow direct comparison with our photometry of M31 GCs Huxor et al. (2008). The $(V - I)$ color for these clusters was measured within a smaller aperture of 4$''$ radius that is chosen to reduce the error from the background and assumes that there is no color gradient in the clusters. For the extended cluster HM33-A, the magnitudes were determined within a larger aperture of 12$''$ radius so

[7] We have learned that HM33-D has also been found by Zloczewski & Kaluzny (2009), in which it has the identifier ZK-90.

[8] IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

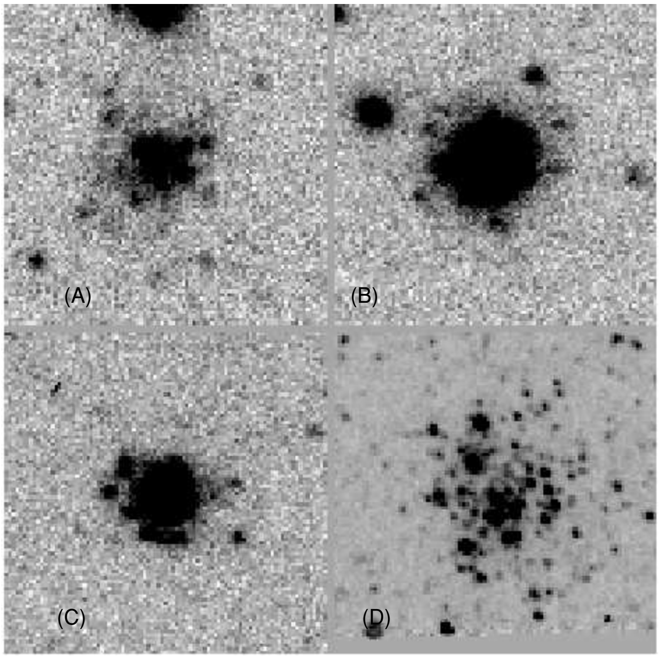


**Figure 2.** Thumbnails ($i$-band) of the outer halo clusters found in the INT-WFC survey (A, B, and C) and in the F606W *HST*/ACS data (D). The INT images span $30'' \times 30''$ while the ACS image spans $7'' \times 7''$. North is up and east is to the left.

as to enclose the bulk of the light. The INT/WFC survey uses Johnson $V$ ($V'$) and Gunn $i$ passbands hence a color transformation was required to obtain the Johnson/Cousins equivalents $V$ and $I$. Following McConnachie et al. (2003), we adopted $V = V' + 0.005(V - I)$ and $I = i - 0.101(V - I)$. Due to the high luminosity of the clusters, the formal errors reported by *apphot* are quite small. The cluster magnitude uncertainties are dominated by the zero-point errors of ∼0.02 mag while color errors are estimated to be ∼0.03 mag. These errors do not account for contamination from foreground stars or background galaxies as these are difficult to estimate. Finally, the cluster magnitudes and colors were corrected for extinction by interpolating within the Schlegel et al. (1998) maps[9] to the position of each cluster. The INT/WFC clusters have absolute magnitudes in the range $M_{V_0} \sim -6$ to $-7$ placing them near the peak of the GC luminosity function.

For the *HST*/ACS cluster, we followed a similar procedure to that of Sarajedini et al. (2006). First, the F606W drizzled image was convolved with a Gaussian kernel ($1\,\sigma = 20$ pixels) as otherwise the light distribution was too patchy to determine the cluster center by eye or by fitting a Gaussian. Once the center was determined, magnitudes were measured on two of the drizzled subimages produced by the STScI CALACS pipeline, with total exposures of 5240 and 10480 s for F606W and F814W filters, respectively. We determine fluxes in a circular aperture of radius 3$''$.5; as the cluster lies near the edge of an ACS chip, this was the maximum aperture size that could be chosen which lay entirely on the chip. Interpolating the Schlegel et al. (1998) dust maps to the cluster's position gave a reddening of $E(B - V) = 0.046$. If we adopt the Sirianni et al. (2005) extinction ratios for a G2 star in the ACS/WFC filter system and the most up-to-date ACS zeropoints[10] then the dereddened magnitude and color are $\mathrm{F606W}_0 = 20.46$ and $(\mathrm{F606W}-\mathrm{F814W})_0 = 0.77$. The S/N of these images is very high and the formal uncertainties on the magnitudes are very small. To convert the ACS/WFC magnitudes to the Johnson–Cousins system, we used the synthetic transformations of Sirianni et al. (2005) which gave $V_0 = 20.60$ (with a systematic zero-point error of 0.05 mag) and $(V - I)_0 = 0.92$ mag. This corresponds to a cluster magnitude of $M_{V_0}$ of $-4.09$, the faintest yet known star cluster in M33, and is comparable to the low-luminosity MW cluster Pal 13. Table 1 lists the positional data and corrected photometry for all clusters.

## 4. DISCUSSION

In the following, the newly discovered clusters are compared with the known cluster population in M33. For this purpose, we use a subset of 167 of the 296 "high-confidence" clusters in the SM07 catalog that have both $V$ and $I$ magnitudes available. We corrected this sample for extinction by interpolating within the Schlegel et al. (1998) dust maps to the position of each cluster. This resulted in a range of $A_V$ from 0.14 to 0.66. We do not use the ZKH08 sample in these comparisons as the authors note that the new GCs in their catalog are only "probable," and may contain contaminants.

Figure 3 shows the location of the new star clusters on a plot of $V_0$ magnitude versus $(V - I)_0$ color. There is a broad spread in magnitudes at all colors and the new objects sit comfortably within this distribution. On the other hand, the *HST*/ACS cluster is far fainter than any previously confirmed M33 star cluster. However, the color of HM33-D, combined with its compact appearance on the *HST*/ACS images, supports its identification as an intermediate or old age GC. This conclusion is further strengthened by the isochrone fits to the color–magnitude diagram which indicate an age of $\gtrsim$3 Gyr and [M/H] $\gtrsim -0.7$ dex (M. K. Barker et al. 2009, in preparation). The existence of such a cluster supports the notion that a population of very faint GCs may await discovery in deeper panoramic imaging of the outskirts of M33.

9 http://astro.berkeley.edu/∼marc/dust/data/data.html

10 http://www.stsci.edu/hst/acs/analysis/zeropoints

**Table 1**
Basic Data for the New Outlying GCs

| ID | R.A. (J2000) | Decl. (J2000) | $V_0$ (mag) | $(V - I)_0$ (mag) | $A_V$ (mag) | Projected Galactocentric Radius (kpc) | Deprojected Galactocentric Radius (kpc)[a] |
|---|---|---|---|---|---|---|---|
| HM33-A | 01 35 41.78 | +28 49 15.5 | 18.60 | 0.83 | 0.26 | 28.6 | 37.7 |
| HM33-B | 01 36 02.12 | +29 57 49.4 | 17.59 | 0.89 | 0.17 | 12.8 | 20.4 |
| HM33-C | 01 37 14.46 | +31 04 27.8 | 18.17 | 0.93 | 0.18 | 12.7 | 17.1 |
| HM33-D | 01 35 02.20 | +31 14 21.3 | 20.60 | 0.92 | 0.13[b] | 9.6 | 9.6 |

**Notes.**
[a] Deprojected values calculated assuming $i = 56$ deg and P.A. = 23 deg.
[b] Extinction in F606W.

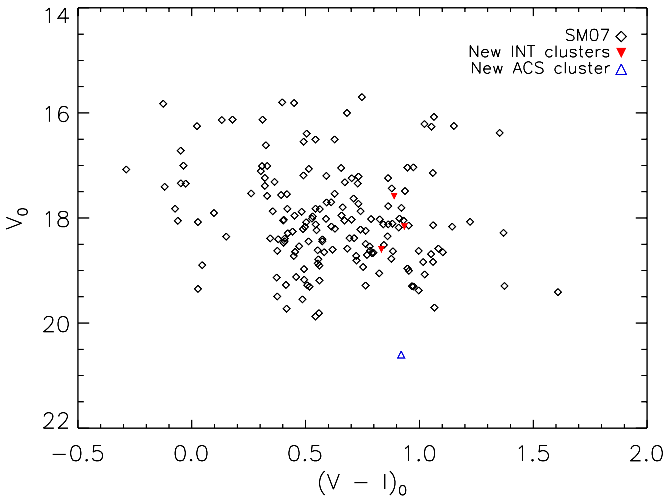


**Figure 3.** Plot of extinction-corrected color vs. apparent magnitude for the new INT/WFC clusters (inverted triangles), the new ACS cluster (triangle), and the "high-confidence" SM07 sample (open diamonds).

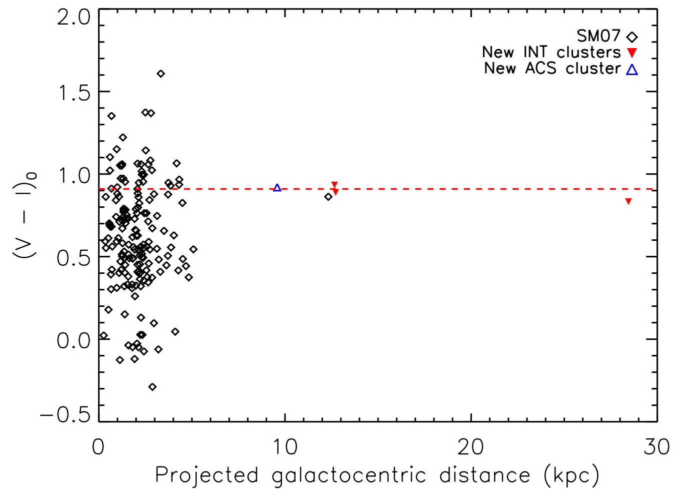


**Figure 4.** Plot of the extinction-corrected color vs. radius for the cluster population in M33. The dashed line indicates the mean extinction-corrected color of the outer halo GCs in the MW and M31 from Huxor et al. (2009).

Our newly discovered clusters, along with that of Stonkutė et al. (2008), show a notable lack of spread in $(V - I)_0$ color when compared to the remaining M33 cluster population. This is particularly apparent when $(V - I)_0$ color is plotted against projected radial distance from M33 (Figure 4). The new clusters are slightly redder than the overall cluster population having an average $(V - I)_0$ color of $0.88 \pm 0.05$ compared to the average $(V - I)_0$ for the inner population being $0.67 \pm 0.30$ mag. The large spread in color at smaller radii is not surprising since the SM07 sample contains many young clusters, which have bluer colors than typical old GCs, and reddening issues will be more problematic here. The colors of the five outermost clusters in Figure 4 are very similar to those of M31 halo GCs with projected radii greater than 30 kpc, which have a mean value for $(V - I)_0 = 0.91 \pm 0.15$, as well to Milky Way clusters beyond 15 kpc, which have $(V - I)_0 = 0.92 \pm 0.12$ (Huxor et al. 2009). That the MW and M31 outer halo GCs are generally old ($\gtrsim$10 Gyr) and metal-poor ([Fe/H] $\lesssim -1.5$; Harris 1996; Mackey et al. 2006, 2007) supports the idea that the new M33 halo clusters are archetypical GCs too, albeit with clusters HM33-A and M33-EC1 having more extended structures. Indeed, Stonkutė et al. (2008) were able to place some constraints on the age and metallicity of M33-EC1 from analysis of their color–magnitude diagram, finding an age $\gtrsim$7 Gyr and [M/H] $\lesssim -1.4$.

Finally, it is notable that so few luminous objects have been discovered in the $\sim$12 deg$^2$ area we have surveyed around M33 (Figure 1). Ignoring the central square degree of our survey which was not searched for new objects due to the presence of the bright disk, we calculate a GC surface density of $\approx$0.4 deg$^{-2}$ in the outskirts of M33 which is almost half that derived for the GC surface density in M31 over the radial range 30–100 kpc (Huxor et al. 2009). Given the extent of the M33 survey area, we can be confident that we have found most of the luminous GCs in the outer halo of the galaxy, although it is possible that a population of small, compact and faint clusters, such as the example found in our *HST*/ACS imagery, still remains to be uncovered. It is also rather interesting that the outermost clusters in M33 are all projected on the far side of the galaxy with respect to M31, despite the survey coverage being essentially uniform. Assuming that the outermost clusters are moving on circular orbits with velocities of 80 km s$^{-1}$, typical of the old halo population identified in the inner regions of M33 (Chandar et al. 2002), their orbital times will be $\sim$ 1–2 $\times 10^9$ yr raising the question as to whether their present spatial configuration can be long-lived or just a chance coincidence. The clear asymmetry in the outer cluster distribution could be a signature that tidal stripping by its larger neighbor may have dramatically affected the GC distribution in M33. On the other hand, this may just be a chance alignment. Line-of-sight distances, radial velocities, and sensitive cluster searches at larger radii will be required to test these ideas further.

## 5. SUMMARY

In this paper, we have presented the discovery of four new outlying star clusters in M33 using INT/WFC survey data and deep *HST*/ACS imagery. Three of these clusters are compact while one is of the extended class. These objects, which have projected radii of 38–113 arcmin or 9.6–28.5 kpc (for an assumed M33 distance of 870 kpc), lie significantly beyond all but one of the currently confirmed star clusters in M33. Their colors and magnitudes are typical of the intermediate-age to old M33 GC population, as well as old age GCs in the far outskirts of the MW and M31. The surface density of halo GCs beyond the optical disk of M33 is roughly one half of that measured in M31 in the radial range $\sim$30–100 kpc. The new clusters have a strikingly asymmetric distribution around M33, all lying on the far side of the galaxy with respect to M31. Further observations are required to properly characterize the stellar populations of these new objects and determine their line-of-sight distances and kinematics.

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*Facilities:* INT (WFC), *HST* (ACS)

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