Globular clusters in the stellar stream surrounding the Milky Way analog NGC 5907

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ABSTRACT
We study the globular clusters (GCs) in the spiral galaxy NGC 5907 well-known for its spectacular stellar stream – to better understand its origin. Using wide-field Subaru/Suprime-Cam gri images and deep Keck/DEIMOS multi-object spectroscopy, we identify and obtain the kinematics of several GCs superimposed on the stellar stream and the galaxy disk. We estimate the total number of globular clusters in NGC 5907 to be \(154 \pm 44\), with a specific frequency of \(0.73 \pm 0.21\). Our analysis also reveals a significant, new population of young star cluster candidates found mostly along the outskirts of the stellar disk. Using the properties of the stream GCs, we estimate that the disrupted galaxy has a stellar mass similar to the Sagittarius dwarf galaxy accreted by the Milky Way, i.e. \(\sim 10^8 \, M_\odot\).

Key words: galaxies: individual NGC 5907 – galaxies: evolution – galaxies: interactions – star clusters: globular clusters

1 INTRODUCTION

In the paradigm of hierarchical galaxy growth over cosmic time, it is expected that the signatures of disrupted, and disrupting, satellites will be present in galaxy halos (Bullock & Johnston 2005). Witnessing the ongoing disruption of a satellite galaxy in the nearby Universe is rare due to the low frequency of occurrence combined with observational challenges given that the surface brightness of the debris declines significantly with time (see Johnston et al. 2001). Nevertheless a few nearby examples are known (e.g. Malin & Hadley 1997; Forbes et al. 2003; Mihos et al. 2005; Tal et al. 2009; Duc et al. 2015), including notable contributions from amateur telescopes (Martinez-Delgado et al. 2008, 2010; Karachentsev et al. 2014).

One of the most prominent examples is the stream associated with a disrupting satellite around the edge-on Milky Way analog, NGC 5907. It was originally imaged by Shang et al. (1998) but is perhaps best known from the deep imaging of Martinez-Delgado et al. (2008). This latter work shows several loops around the galaxy. Laine et al. (2016) focused on the brightest part of the stream which lies to the NE of NGC 5907, extending out to \(\sim 65\) kpc as shown in Figure 1. Most recently deep imaging using the Dragonfly telephoto array has revealed a different view with a single long stream stretching from the NE to the SW of the galaxy (van Dokkum et al. 2019). It is not clear why the Dragonfly imaging differs from that of Martinez-Delgado et al. (2008).

Similarly, details of the progenitor satellite responsible for the stellar stream(s) in NGC 5907 are still poorly defined, with the inferred mass of the disrupted satellite galaxy varying in the literature. The study of Laine et al. (2016), based on stellar populations in the NE stream, concluded that the stellar mass of the disrupting satellite was \(\sim 10^{10} \, M_\odot\), i.e., a 1:10 minor merger. This is considerably larger than the mass of \(\sim 10^8 \, M_\odot\) in the semi-analytic modeling of Johnston et al. (2001) and the N-body models of Martinez-Delgado et al. (2008) and van Dokkum et al. (2019). Wang et al. (2012) also used a 1:3 gas-rich major merger to model the stellar loops in NGC 5907. Thus it is currently uncertain whether the satellite debris results from a major, minor, or intermediate mass merger.

To further constrain the mass of the progenitor satellite, line-of-sight velocities along the stellar stream(s) are therefore required (e.g. Lynden-Bell & Lynden-Bell 1995; Dinescu et al. 1999). Given the faint surface brightness of even the brightest loop ((\(\mu_v\) \sim 27.6 mag arcsec\(^{-2}\)), this is extremely challenging. An alternative is to use globular clusters (GCs) in the stream as proxies. Such an approach was successfully applied by Foster et al. (2014) to probe the nature of a 1:50 stellar mass ratio merger in the Umbrella galaxy NGC 4651. Similarly, the outer halo GCs in the Galaxy and M31 have been shown to trace the remnants of disrupted satellites (Mackey et al. 2010; Massari et al. 2019). For a satellite with stel-

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lar mass $10^6$ to $10^{10} M_\odot$, the number of associated GCs could be as low as 1 or as high as 100 (Forbes et al. 2018).

Identifying suitable GC candidates in spiral galaxies is challenging. This is mostly due to issues such as dust, disk, and bulge obscurations, and their numerically poor GC systems. For example, Harris et al. (1988) reported a non-detection of GCs in NGC 5907 from their ground-based observations. Kissler-Patig et al. (1999), using HST/WFPC2, detected 25 GCs near the disk of NGC 5907, although their imaging did not extend into the stream area. After a correction for spatial incompleteness based on the Milky Way’s GC system, they estimated a total GC system of $170^{+47}_{-72}$.

In this study, we present wide-field Subaru imaging of NGC 5907 and Keck spectroscopy of several GC candidates. We assume a distance of 17 Mpc to NGC 5907, as adopted by Laine et al. (2016) and summarize salient properties of NGC 5907 in Table 1. Many of its properties are similar to those of the Milky Way. The paper is organized as follows: Section 2 describes the imaging data, source detection, photometry, and spectroscopic data. In Section 3, we present our results including the catalog of GC candidates, young star cluster candidates, and stream GCs. We conclude by discussing the implications of our results in Section 6.

2 DATA

2.1 Observations

The imaging used for this work was obtained using the wide-field Suprime-Cam imager on the 8.2m Subaru telescope with the SDSS gri filters under photometric conditions (0\arcsec.6–0\arcsec.9 seeing). Details of the observations and data reduction are explained in Laine et al. (2016). The imager has a total field-of-view of 34′×27′ with a pixel scale of 0\arcsec.2 per pixel.

In Figure 1 we show our color composite image of NGC 5907. It clearly shows the NE stellar stream but it is lacking the extension...
to the SW seen by van Dokkum et al. (2019) and the E1 and E2 loops of Martínez-Delgado et al. (2008). The surface brightnesses along the faintest section of the stream (E2 in Figure 1) are 28.5, 28.0, and 27.8 mag arcsec$^{-2}$ in our g, r, and i imaging, respectively.

### 2.2 Image preparation

For optimal point-source detection, the galaxy light and other large scale structures need to be removed from the raw $gri$ images. This is done by subtracting a model of the galaxy bulge and disk, obtained with G AL FIT (Peng et al. 2002) from the raw images before applying a median filter to remove large scale residual features with the ring median filter algorithm described in Secker (1995). This method efficiently produces a galaxy image with minimal residuals (down to the galaxy center) suitable for point-source detection.

We subtract the median-filtered image\(^1\) from the galaxy-subtracted images and add back the background counts for accurate photon statistics. We call the output of this process our “cleaned” images.

### 2.3 Source Detection

Source detection was performed on our “cleaned” $gri$ images with S EXTRACTOR (Bertin & Arnouts 1996). We detect and perform aperture photometry on 14692 sources common to our $gri$ images. Extended sources (i.e., background galaxies) are removed from our catalog using the following criteria and fine-tuning the steps to accommodate as many as possible of the previously reported GC candidates detected in H ST imaging (Kissler-Patig et al. 1999):

- S EXTRACTOR FLAG parameter > 0,
- CLASS_STAR parameter < 0.3, and
- all FWHM > 8 pixels,

This process gives 5947 point-sources remaining.

We convert our instrumental magnitudes (MAG_AUTO from S EXTRACTOR) to the SDSS photometric system using bright point-sources ($17 < g < 21$) in common with our catalog. Finally, Galactic extinction corrections in the direction of NGC 5907 from the dust reddening maps of Schlafly & Finkbeiner (2011) are applied to our point-source catalog to obtain extinction-corrected magnitudes in each band. The corrections applied are $A_g = 0.035$, $A_r = 0.024$, and $A_i = 0.018$. No internal reddening correction is applied.

\(^1\) median-filtered images were created with the MEDIAN task in IRAF using inner and outer radii of 5 and 9 times the FWHM of point sources in the images.

### 2.4 Photometric Completeness and Magnitude Limits

To understand how well we detect point-sources as a function of magnitude, we artificially added 600 point-sources to our “cleaned” images, with magnitudes uniformly spread over the range 18 $< m_g < 26.5$. We then performed source detection as described above, noting the fraction of point-sources recovered. We repeated this experiment 60 times per filter (adding a total of 36000 artificial point-sources) and show the recovered fraction as a function of magnitude, highlighting the 50% and 80% completeness levels, in Figure 2. Due to the high variability of the residual background in the disc region after subtracting off the galaxy light, the recovered fraction is typically less than 100% in the bright magnitude range, i.e., $20 < m_g < 23$. Our photometry is 50% complete at $g = 24.8$, $r = 24.6$, and $i = 24.3$, respectively.

We use the 80% completeness magnitude in the $i$-band (i.e., $i = 23.8$), where detection starts to fall off sharply, to define the faint limit of our photometry. Likewise, we define a bright magnitude limit based on the magnitude of the brightest GC in the Galaxy, $M_g = -11.0$ (see a similar application in Pota et al. 2015), using a distance modulus $m - M = 31.15$. Applying this bright magnitude limit to our catalog ensures that all point-sources brighter than the most luminous GCs in the MW are excluded from subsequent analysis. This brings the number of point-sources to 3798. At this stage, our point-source catalog includes 11 objects out of the 25 H ST-detected GC candidates (Kissler-Patig et al. 1999). We have also checked the stream region for objects which are brighter than our bright magnitude limit and found none. Such objects could be viable candidates for the nucleus of the disrupted satellite galaxy.

### 2.5 Selection of Globular Cluster Candidates

Figure 3 shows the $(g - i)$ vs $(r - i)$ color–color plot of all the point-sources detected in NGC 5907. Since GCs are known to occupy distinct regions in color–color space (e.g., Rhode & Zepf 2003; Pota et al. 2013; Muñoz et al. 2014), their colors can be used as powerful tools for discriminating them from co-spatial foreground stars and background galaxies. We use the compilation of Milky Way GCs from Harris (1996, 2010 edition) to outline the region that GCs occupy in color–color space after converting their BVR photometry to SDSS $gri$ using the transformation equations from Jester et al. (2005) and correcting for reddening. The transformed

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**Table 1. Properties of NGC 5907**

| Property          | Value      | Reference     |
|-------------------|------------|---------------|
| Hubble type       | Sc         | NED           |
| $M_V$             | $-20.81$   | NED           |
| Stellar mass      | $1 \times 10^{11}$ M$_\odot$ | Posti et al. (2019) |
| Total gas mass    | $8.6 \times 10^9$ M$_\odot$ | Just et al. (2006) |
| Disc scale length | 5.5 kpc    | Just et al. (2006) |
| Disc cutoff radius| 19.7 kpc   | Just et al. (2006) |
| Distance          | 17 Mpc     | Tully et al. (2016) |
| $V_{esc}$         | 226.7 km s$^{-1}$ | Makarov et al. (2014) |
| $V_{sys}$         | 667 km s$^{-1}$ | Tully et al. (2016) |
| PA                | 155$^\circ$ | Jarrett et al. (2003) |
| Inclination       | 88$^\circ$ | Just et al. (2006) |
and dereddened \((g - i)\) and \((r - i)\) Milky Way GC colors range from 0.27 to 1.15 and 0.13 to 0.41, respectively, with [Fe/H] spanning from -2.5 to 0.

Point-sources are selected as GC candidates if they have \(i\) band magnitudes ranging from 20.05 to 23.9, and \(g - i\) and \(r - i\) colors similar to the Milky Way GCs. We also visually checked these GC candidates, excluding the obvious background galaxies. Using these criteria, our GC candidate catalog now has 703 members at an 80% completeness level in the \(i\) band. Out of the 11 point-sources in common with the \(HST\)-detected GC sample from Kissler-Patig et al. (1999), only 7 qualify as GC candidates based on our color and magnitude selection criteria. The remaining 4 \(HST\)-detected objects have red colors that lie outside our GC color–color selection region.

While our GC selection here is based on the assumption that the GC system of NGC 5907 is similar to that of the Galaxy, we note that we obtain a similar result if we define our selection region using the GC system of M31 (e.g., Chen et al. 2016). We provide a complete summary of all the various classes of point-sources detected in this work in Table 2.

### Figure 3.

Color–color selection of GC candidates around NGC 5907. In the left panel, the region occupied by Milky Way GCs is used to define a GC selection region (the black ellipse) in color–color space. The Milky Way GCs are shown as filled circles and they are color-coded by their metallicities. The selection region contains 703 GC candidates. In the right panel, we show the spectroscopically confirmed GCs around NGC 5907 as black squares, spectroscopic stars as teal diamonds, and the GC candidates that were also detected in the \(HST\) sample from Kissler-Patig et al. (1999) as blue crosses. Some of the spectroscopically confirmed point-sources fall outside our GC selection region due to internal reddening and a few are very blue (they may be compact, young star clusters).

### Figure 4.

Stacked spectra (S/N= 12) of the confirmed globular clusters in NGC 5907 highlighting the \(H\alpha\) (blue band) and Calcium triplet (red bands) spectral regions.

#### 2.6 Keck Spectroscopy of point-sources around NGC 5907

Using our point-source catalog, we identified target point-sources for follow-up spectroscopy with the DEIMOS spectrograph on the Keck II telescope. We obtained three masks; one along the bright NE loop, one covering the E1 and E2 loops of Martínez-Delgado et al. (2008), with the last mask positioned along the disk of NGC 5907. In total we placed slits on 359 point-sources as shown in Figure 5. Data were obtained on the nights of 2013 April 10, 2016 March 10 and 2017 April 27 for a total of 6.5 hours. We used both the 600 lines/mm grating (centered on 6700 Å) and the 1200 lines/mm grating (centered on 7800 Å). Spectra were reduced using the \texttt{spec2d} pipeline and the same procedure as successfully applied during the SLUGGS survey (e.g., Pota et al. 2013; Forbes et al. 2017). We measured line-of-sight velocities \((V_{\text{los}})\) from the \(Ca\text{T}\) and \(H\alpha\) spectral features with \texttt{FXCOR} in IRAF using stellar templates from the MILES spectral library (Vazdekis et al. 2016).

Assuming that all point-sources with measured \(V_{\text{los}} < 300\) km s\(^{-1}\) are foreground stars, we identify 11 point-sources belonging to NGC 5907 \((V_{\text{los}} = 667\) km s\(^{-1}\)) and/or the stream, and 64 objects as Milky Way stars. These 11 point-sources have \(300 \leq V_{\text{los}}\) (km s\(^{-1}\)) \(\leq 920\) and \(21.6 \leq i \leq 23.1\) with S/N per Å varying from 5–7, but they are not all bona fide GCs as we show in Section 4. The foreground stars are relatively brighter, having \(19.1 \leq i \leq 23.5\). One of the objects which we have classified as a star has \(V_{\text{los}} = 298\) km s\(^{-1}\), very close to the limit we used to separate foreground stars from objects belonging to NGC 5907. However, it has both \(g - i\) and \(r - i\) colors outside the range we have used to define GCs and we therefore classify it as a foreground star. All other objects fall securely within the limits defined above. In addition, we also confirm 7 background galaxies with redshifts \((z) \geq 0.01\) in the direction of NGC 5907. We show the projected phase-space distribution of the point-sources belonging to NGC 5907 in Figure 6 while we summarize all the point-sources with line-of-sight velocity measurements in Table 2. All spectroscopically confirmed foreground stars and background galaxies have been manually removed from our final GC catalog.

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Out of the 11 spectroscopically confirmed point-sources associated with NGC 5907 (Section 2.6), only 8 appear to be GCs. Two, seen in projection near the galaxy disk, have very blue colors ($g-i \leq-0.1$) and are probably young star clusters (see Section 4). The remaining point-source, which we exclude from further analysis, could be a bona fide GC but it has a very red color ($g-i \sim 1.6$) probably due to internal dust reddening and lies outside our GC color–color selection region. Since the HST study imaged the disk only, we are unable to spectroscopically confirm any of the HST-detected GC candidates. It is particularly noteworthy that none of the 11 spectroscopically confirmed point-sources lie along the fainter E1 and E2 loops.

3 RESULTS

3.1 Total number of Globular Clusters in NGC 5907

In order to obtain an estimate of the total number of GCs in NGC 5907, we need to account for the undetected GCs in the galaxy central region where the galaxy-light subtracted background varies anisotropically and also estimate the contaminants that might remain in our GC candidate catalog.

3.1.1 Detection incompleteness in the galaxy central region

Within the region common to the HST study, our GC detection is a factor of ~ 2 incomplete relative to the Kissler-Patig et al. (1999) sample. This incompleteness in detection implies that our GC catalog would be biased against the red GCs which are expected to dominate the galaxy central regions. We follow the method introduced by Kissler-Patig et al. (1999) to estimate the number of undetected GCs within the region of maximum obscuration where we detect only 19 GC candidates. If we assume that GCs in NGC 5907 and the Milky Way have similar spatial distributions, we estimate that 75 GCs should be observed in this central region. We arrive at this estimate after projecting this region on the Milky Way GC system at the distance and orientation of NGC 5907 and also applying our magnitude incompleteness correction.

3.1.2 Foreground and Background contamination

We leverage the wide-field nature of our imaging to determine the contamination within our GC candidate catalog. Results from Section 2.6, where we found a low return rate of point-sources belonging to NGC 5907 (i.e. 11 out of a total of 83), already suggest a
Figure 6. Projected phase-space distribution of the 11 point-sources belonging to NGC 5907. The gray filled circles are point-sources spatially associated with the stellar stream (GC3, GC5, and GC7) while the black filled circles are mostly near the galaxy disk. The dashed curves show the velocity limits consistent with the circular velocity of NGC 5907 assuming a logarithmic potential. The distribution of the stream GCs in phase-space is “chevron-like”, consistent with expectations for cold kinematic substructures.
However they have very blue colors (g − i < 0.3, r − i < 0.1) and occupy the same region in color–color space as the young star clusters (YC) identified in M31 (e.g. Peacock et al. 2009; Chen et al. 2016). We identify 34 such point-sources as YC candidates, with 14 of them spatially aligned along the outskirts of the galaxy disk as shown in Figure 5. Figure 8 shows color-magnitude diagrams of our point-sources highlighting the young star cluster candidates. We note that similar to M31, the young clusters are systematically fainter than the globular clusters, suggesting that they may be less massive (Caldwell et al. 2009; Peacock et al. 2009).

It is not obvious whether or not these YCs are part of a structure similar to the well-known “ring of fire” identified in M31 (e.g., Brinks & Burton 1984). There is however evidence that the two YC candidates with radial velocity measurements (see Figure 5) are consistent with the overall disk rotation. Their line-of-sight velocities (460 and 476 km s$^{-1}$) are consistent with the rotational velocity (480 km s$^{-1}$) of the approaching arm from the HI velocity map (Sancisi 1976). Unfortunately, we do not have YCs spatially coincident with the receding arm.

In their study of the stellar stream in NGC 5387, Beaton et al. (2014) found a very-blue, young stellar overdensity at the intersection of the stream with the galaxy disk. They interpreted their result as evidence for either an induced star formation in the disk outskirts due to the satellite accretion event or starburst in the stream progenitor. Laine et al. (2016), in a stellar population study of the stellar stream in NGC 5907, reported no such stellar over-density nor did they find any blue star-forming regions. However it is evident from their figures 3 and 4 that they did not probe out to the region where we have observed these YCs.

**4 YOUNG STAR CLUSTERS IN NGC 5907**

An examination of the spatial distribution of the point-sources from Section 2.4 reveals an over-density at the intersection of the most prominent (NE) stellar loop with the galaxy disk. Visual inspection of these point-sources show that they are similar to GC candidates and two of them have been spectroscopically confirmed as members of NGC 5907, with line-of-sight velocities similar to the GCs. However they have very blue colors (g − i < 0.3, r − i < 0.1) and occupy the same region in color–color space as the young star clusters (YC) identified in M31 (e.g. Peacock et al. 2009; Chen et al. 2016). We identify 34 such point-sources as YC candidates, with 14 of them spatially aligned along the outskirts of the galaxy disk as shown in Figure 5. Figure 8 shows color-magnitude diagrams of our point-sources highlighting the young star cluster candidates. We note that similar to M31, the young clusters are systematically fainter than the globular clusters, suggesting that they may be less massive (Caldwell et al. 2009; Peacock et al. 2009).

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**5 STREAM GLOBULAR CLUSTERS IN NGC 5907**

In this Section, we focus our attention on the 3 spectroscopically confirmed GCs that are seen in projection along the most prominent NE stellar loop (i.e., GC3, GC5 and GC7). Figure 6 already shows that these stream GCs have the “chevron-shaped” distribution in phase-space that is usually associated with kinematic substructures (e.g. Romanowsky et al. 2012). These GCs have g − i colors varying from 0.78 to 0.83 which corresponds to a mean [Fe/H] = −1.15 ± 0.1. We inferred this metallicity from a linear fit to the transformed g − i colors and [Fe/H] of the Milky Way GC sample bearing in mind the recently reported variations in the GC color–[Fe/H] relation from galaxy to galaxy (Villaume et al. 2019). Our inferred GC mean metallicity implies that the stellar mass of the progenitor galaxy is 10$^9$ M$_\odot$, similar to the Sagittarius dwarf galaxy, using the stream GC metallicity–stellar mass relation from the E-MOSAICS simulations of Hughes et al. (2019). The stacked spectra shown in Figure 4 has a S/N per Å of ∼ 12 with strong Calcium triplet features consistent with typically old, metal-poor stellar populations. Assuming that GCs associated with the stellar streams all have similar colors, we find 4 other plausible stream GC candidates (all along the NE loop) in our final catalog (see Table 2). These four objects, which lack spectroscopic confirmation, are highlighted in Figure 8 and are shown superimposed on the NE stellar loop in Figure 9 and should be the subject of a follow-up spectroscopic study.
imaging analysis of NGC 5907 in which they also found no evidence of fainter loops as well as those photometrically identified on the NE loop but spectroscopically find none along the fainter E1 and E2 loops. We also spectroscopically confirm five GCs spatially associated with the galaxy disk, and identify a new population of very blue, young star clusters mostly in the outskirts of galaxy disk, of which we spectroscopically confirm two. We provide an online catalog of all the detected sources in this work.

A deeper spectroscopic study of the GC candidates on the fainter loops as well as those photometrically identified on the NE loop is required to unambiguously resolve the nature and origin of the spectacular stellar stream in NGC 5907. This will allow for a straightforward comparison with the recent predictions from the E-MOSAICS cosmological simulations (Hughes et al. 2019) and various N-body models. Likewise, detailed stellar population study of the young star cluster candidates identified in this work is needed.

7 NOTE ADDED IN PROOF
After this paper was accepted, Miller et al. (2019) presented a deep imaging analysis of NGC 5907 in which they also found no evidence of the E1 and E2 loops.

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REFERENCES
Beaton R. L., et al., 2014, ApJ, 790, 117
Bertin E., Arnouts S., 1996, A&AS, 117, 393
Brinks E., Burton W. B., 1984, A&A, 141, 195
Bullock J. S., Johnston K. V., 2005, ApJ, 635, 931
Caldwel L., Harding P., Morrison H., Rose J. A., Schiavon R., Kriessler J., 2009, AJ, 137, 94
Chen B., et al., 2016, AJ, 152, 45
Dinescu D. I., Girard T. M., van Altena W. F., 1997, PASA, 14, 52
Duc P.-A., et al., 2015, MNRAS, 446, 120
Forbes D. A., Beasley M. A., Bekki K., Brodie J. P., Strader J., 2003, Science, 301, 1217
Forbes D. A., et al., 2017, AJ, 153, 114
Forbes D. A., Read J. I., Gieles M., Collins M. L. M., 2018, MNRAS, 481, 5592
Foster C., et al., 2014, MNRAS, 442, 3544
Harris W. E., 1996, AJ, 112, 1487
Harris H. C., Bois G. D., Hesser J. E., 1988, in Grindlay J. E., Philip A. G. D., eds, IAU Symposium Vol. 126, The Harlow-Shapley Symposium on Globular Cluster Systems in Galaxies. p. 613
Hughes M. E., Pfeffer J., Marig M., Bastian N., Crain R. A., Kruijssen J. M. D., Reina-Campos M., 2019, MNRAS, 482, 2795
Jarrett T. H., Chester T., Cutri R., Schneider S. E., Huchra J. P., 2003, AJ, 125, 525
Jester S., et al., 2005, AJ, 130, 873
Johnston K. V., Sackett P. D., Bullock J. S., 2001, ApJ, 557, 137
Just A., Mollenhoff C., Borch A., 2006, A&A, 459, 703
Karachentsev I. D., Bautzmann D., Neyer F., Polzl R., Reip P., Zilch T., Mattern B., 2014, arXiv e-prints, p. arXiv:1401.2719
Kissler-Patig M., Ashman K. M., Zepf S. E., Freeman K. C., 1999, AJ, 118, 197
Laine S., et al., 2016, The Astronomical Journal, 152, 72
Lynden-Bell D., Lynden-Bell R. M., 1995, MNRAS, 275, 429
Mackey A. D., et al., 2010, ApJ, 717, L11
Makarov D., Prugniel P., Terekhova N., Courtois H., Vauglin I., 2014, A&A, 570, A13
Malin D., Hadley B., 1997, PASA, 14, 52
Martínez-Delgado D., Peñarrubia J., Gabany R. J., Trujillo I., Majewski S. R., Pohlen M., 2008, ApJ, 689, 184
Martínez-Delgado D., et al., 2010, AJ, 140, 962

Figure 9. Globular clusters superimposed on the NE stellar loop. Red circles indicate spectroscopically confirmed GCs, and we show their line-of-sight velocities relative to NGC 5907. The white circles are the likely stream GC candidates with no velocity measurement.

6 SUMMARY AND CONCLUSIONS
In this work, we have used wide-field imaging and multi-object spectroscopy to investigate the GCs around the spiral galaxy NGC 5907 and its associated stellar stream from a disrupted satellite. We detect GC candidates out to ∼ 65 kpc from the galaxy center, with most of the spectroscopically confirmed candidates spatially distributed within ∼ 20 kpc of the galaxy disk. We estimate that NGC 5907 has a total of 154 GCs and a specific frequency of ∼ 7. We identify GC candidates along the well-known NE stellar loop but spectroscopically find none along the fainter E1 and E2 loops. We also spectroscopically confirm five GCs spatially associated with the galaxy disk, and identify a new population of very blue, young star clusters mostly in the outskirts of galaxy disk, of which we spectroscopically confirm two. We provide an online catalog of all the detected sources in this work.

A deeper spectroscopic study of the GC candidates on the fainter loops as well as those photometrically identified on the NE loop is required to unambiguously resolve the nature and origin of the spectacular stellar stream in NGC 5907. This will allow for a straightforward comparison with the recent predictions from the E-MOSAICS cosmological simulations (Hughes et al. 2019) and various N-body models. Likewise, detailed stellar population study of the young star cluster candidates identified in this work is needed.
Massari D., Koppelman H. H., Helmi A., 2019, arXiv e-prints, p. arXiv:1906.08271
Mihos J. C., Harding P., Feldmeier J., Morrison H., 2005, ApJ, 631, L41
Muñoz R. P., et al., 2014, ApJS, 210, 4
Miller O., Vudragović A., Blek M., 2019, Hunting ghosts: the iconic stellar stream(s) around NG5907 under scrutiny (arXiv:1911.12577)
Peacock M. B., Maccarone T. J., Waters C. Z., Kundu A., Zepf S. E., Knigge C., Zurek D. R., 2009, MNRAS, 392, L55
Peng C. Y., Ho L. C., Impey C. D., Rix H.-W., 2002, AJ, 124, 266
Posti L., Fraternali F., Marasco A., 2019, A&A, 626, A56
Pota V., et al., 2013, MNRAS, 428, 389
Pota V., et al., 2015, MNRAS, 450, 1962
Rhode K. L., Zepf S. E., 2003, AJ, 126, 2309
Robin A. C., Reylé C., Derrière S., Picard S., 2003, A&A, 409, 523
Romanowsky A. J., Strader J., Brodie J. P., Mihos J. C., Spitler L. R., Forbes D. A., Foster C., Arnold J. A., 2012, ApJ, 748, 29
San complet R., 1976, A&A, 53, 159
Schlafly E. F., Finkbeiner D. P., 2011, ApJ, 737, 103
Secker J., 1995, Publications of the Astronomical Society of the Pacific, 107, 496
Shang Z., et al., 1998, ApJ, 504, L23
Tal T., van Dokkum P. G., Nelan J., Bezanson R., 2009, AJ, 138, 1417
Tully R. B., Courtois H. M., Sorce J. G., 2016, AJ, 152, 50
Vazdekis A., Koleva M., Ricciardelli E., Röck B., Falcón-Barroso J., 2016, MNRAS, 463, 3409
Villaume A., Romanowsky A. J., Brodie J., Strader J., 2019, ApJ, 879, 45
Wang J., Hammer F., Athanassoula E., Puech M., Yang Y., Flores H., 2012, A&A, 538, A121
van Dokkum P., et al., 2019, arXiv e-prints, p. arXiv:1906.11260

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