CLUSTER 77 IN NGC 4449: THE NUCLEUS OF A SATELLITE GALAXY BEING TRANSFORMED INTO A GLOBULAR CLUSTER?*

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ABSTRACT

We report the discovery in our Hubble Space Telescope Advanced Camera for Surveys B, V, and I images of NGC 4449 of a globular cluster (GC) which appears associated with two tails of blue stars. The cluster is massive \((M \sim 1.7 \times 10^6 \, M_\odot)\) and highly flattened \((\epsilon \sim 0.24)\). From the color–magnitude diagrams of the resolved stars we infer active star formation in the tails over the past \(\sim 200\) Myr. In a diagram of mean projected mass density inside \(r_s\) versus total mass the cluster lies at the upper end of the GC distribution, where galaxy nuclei are. The northwest tail is associated with a concentration of H\(^i\) and infrared (dust/polycyclic aromatic hydrocarbons) emission which appears as part of a much longer stream wrapping around the galaxy. These properties suggest that the cluster may be the nucleus of a former gas-rich satellite galaxy undergoing tidal disruption by NGC 4449. If so, the cluster is seen in an earlier phase compared to other suggested nuclei of disrupted galaxies such as \(\omega\) Cen (Milky Way) and G1 (M31).

Key words: galaxies: clusters: individual (NGC 4449:CL 77) – galaxies: dwarf – galaxies: individual (NGC 4449) – galaxies: starburst

Online-only material: color figures

1. INTRODUCTION

Within the hierarchical framework for galaxy formation, accretion and disruption of dwarf galaxies drive the formation of larger galaxy halos (e.g., Helmi & White 1999). This process leaves long-lived relics in the form of streams of stellar remnants that remain aligned to the orbital path of the parent satellite (e.g., Johnston et al. 1996). The closest examples of such processes are the tidal stream of the Sagittarius dwarf spheroidal galaxy (Sgr dSph; Ibata et al. 1994), which is merging with the Milky Way (MW; e.g., Ibata et al. 2001a; Majewski et al. 2003), and the Andromeda (M31) streams (e.g., Ibata et al. 2001b). M54, the second most massive Galactic globular cluster (GC), lies at the photometric center and possibly at the distance of Sgr dSph, and was considered as its nucleus, although there are suggestions that it may actually be \(\sim 2\) kpc in the foreground of the galaxy center (Bellazzini et al. 2008; Siegel et al. 2011).

Stellar streams provide unquestionable evidence of satellite accretion, but there may be less manifest cases in which the former satellite galaxy is no longer identifiable and what remains after the disruption is just a naked nucleus. Two such potential cases are \(\omega\) Cen and G1, the most massive GCs in the MW and M31, respectively, that have been suggested to be nuclei of disrupted galaxies on the basis of the following properties: the presence of multiple stellar populations (e.g., Pancino et al. 2000; Bellini et al. 2010) or of a chemical abundance spread (Johnson & Pilachowski 2010; Meylan et al. 2001); their very flattened shape (Pancino et al. 2000; Meylan et al. 2001); velocity dispersions larger than in other GCs (Djorgovski et al. 1997; Sollima et al. 2009); the dynamical evidence, in G1, for the presence of a central black hole (Gebhardt et al. 2002); the very bound retrograde orbit of \(\omega\) Cen with respect to Galactic rotation (Dinescu et al. 1999); and a tidal plume of stars very near the (projected) position of G1 (Ferguson et al. 2002). Because of the presence of tidal tails, the GC Palomar 14 has also been suggested to be the remnant of an ancient galaxy progressively disrupted by the interaction with the MW (Sollima et al. 2011). Both \(\omega\) Cen and G1 lie in a mean projected mass density versus total-mass diagram, close to the locus of galaxy nuclei (see Figure 3 in Walcher et al. 2005). Galaxy nuclei have very similar properties to GCs (see, e.g., van der Marel et al. 2007) but are more massive than typical GCs, and exhibit mixed-age populations, generally with an underlying old stellar population.

In this Letter, we report the discovery in the starburst irregular galaxy NGC 4449 \((D = 3.82 \pm 0.18\) Mpc) of an old cluster surrounded by two structures of young stars roughly symmetrically located, reminiscent of tidal tails. The cluster \((\alpha_{2000} = 12 \text{h} \, 27 \text{m} \, 57.53 \text{s}, \delta_{2000} = 44 \text{d} \, 05 \text{m} \, 28.16 \text{s})\) is located west at a projected distance of \(\sim 3\) kpc from the galaxy center, has a mass of \(M \sim 1.7 \times 10^6 \, M_\odot\), a luminosity-weighted age of \(\sim 7\) Gyr, and exhibits significant ellipticity \((\epsilon \sim 0.24;\text{ Annibali et al. 2011, hereafter A11})\). These properties suggest that it may be a galaxy nucleus still surrounded by remains of its former parent galaxy.

The star properties in the cluster and in the tails are described in Section 2 through the Hubble Space Telescope (HST)/Advanced Camera for Surveys (ACS) color–magnitude diagrams (CMDs). Archival data of NGC 4449 at other wavelengths (ultraviolet, infrared, radio) are examined in Section 3. We discuss the arguments in favor of and against CL.77 being a nucleus and summarize our results in Section 4.

2. HST DATA AND COLOR–MAGNITUDE DIAGRAMS

NGC 4449 was observed with the Wide Field Channel of the ACS in the F435W (B), F555W (V), F814W (I), and F658N

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blue and T2 contours were outlined following the distribution of the tails (NW tail: T1; SE tail: T2) are shown in Figure 2. The elliptical region (C) around CL 77 and in two regions including the bottom left of the figure. (A color version of this figure is available in the online journal.)

Figure 1 shows a color-combined image centered on CL 77 and including the blue tails. The cluster is partially resolved into stars at its outskirts in the B image, but it is only poorly resolved in the $V$ image. The CMDs of the stars resolved in an elliptical region (C) around CL 77 and in two regions including the tails (NW tail: T1; SE tail: T2) are shown in Figure 2. The T1 and T2 contours were outlined following the distribution of the blue/yellow stars in Figure 1 and in the bottom left panel of Figure 3. The cluster stars are almost all red giant branch (RGB) stars (top right panel of Figure 2). A comparison with a nearby field indicates no significant difference between the properties of the two RGBs. The CMD confirms that CL 77 is older than $\sim 1$ Gyr (as inferred from the integrated colors in A11) and shows that the RGB color is consistent with a metallicity of $Z \sim 0.004$, as for the field RGB stars (see A08 and CMDs in the middle and lower panels of Figure 2).

The CMDs of T1 and T2 are shown in the middle and lower panels of Figure 2, respectively, with the $Z = 0.004$ Padova isochrones (Girardi et al. 2010) superimposed. Both diagrams display old (age $\sim 1$ Gyr) RGB stars, as well as populated “blue plumes” at $V - I, B - V \sim -0.1$ and red supergiants, indicative of recent star formation (SF). In T1, the blue plume is well populated up to $V \sim 22.5$, and there are a few blue supergiants as bright as $V \sim 21$; the red supergiants at $1.2 \lesssim B - V \lesssim 1.8$ and $21 \lesssim V \lesssim 22.5$ are consistent with ages between 50 and 20 Myr ago. The blue loop and asymptotic giant branch (AGB) phases for ages between $\sim 50$ Myr and 1 Gyr appear scarcely populated, suggesting that the SF was not very active in T1 at ages older than $\sim 50$ Myr. In T2, the bulk of the recent SF seems to be older than in T1 because the drop in the blue luminosity function occurs at a fainter magnitude ($V \sim 24$) than in T1. In T2, we also observe a concentration of AGB stars at $1.4 \lesssim B - V \lesssim 1.8$ and $22.5 \lesssim V \lesssim 23.5$, corresponding to isochrones of ages between $\sim 200$ and $\sim 50$ Myr. This clearly identifies a burst of SF that occurred in T2 between $\sim 200$ and $\sim 50$ Myr ago. The SF possibly continued at a lower level until $\sim 20$ Myr ago. The CMDs indicate a lower level of SF between $\sim 200$ Myr and $\sim 1$ Gyr ago.

We attribute the old (>1 Gyr) RGB stars in T1 and T2 to the NGC 4449 field. In fact, as shown in the bottom right panel of Figure 3, there is no evidence for an overdensity of old stars in correspondence of the tails.

### 3. DATA AT OTHER WAVELENGTHS

Figure 3 shows, on the same scale as our I ACS mosaiccd image, the FUV (Galaxy Evolution Explorer, GALEX), 8.0 μm (Spitzer), and H I (Very Large Array, VLA) images. The FUV data are from the 11HUGS survey (Lee et al. 2004) and trace stars younger than $\sim 100$ Myr. The 8.0 μm image, which traces polycyclic aromatic hydrocarbons (PAHs), belongs to the Spitzer Local Volume Legacy survey (Dale et al. 2009). The H I integrated intensity map is from the THINGS survey (Walter et al. 2008). We also show in Figure 3 density maps of the resolved stars younger than 100 Myr and older than 1 Gyr derived from the CMDs in A08.

In the FUV, the tails around CL 77 appear as two diametrically opposed, symmetric structures on which the cluster is centered. However, the 8 μm and H I images show that they are in fact not symmetric: while T2 does not appear very prominent in these bands, T1 is associated with significant emission at 8 μm (as well as at longer infrared wavelengths, not shown here), with one of the brightest H I spots in the whole galaxy, and also with ionized gas (see Figure 1 in Hunter et al. 2005). Figure 4 shows that the peak of H I is offset with respect to the stars in T1 and to the infrared emission (and also with respect to the ionized gas). From the integrated H I map, and using Equations (1) and (5) in Walter et al. (2008), we estimate an average column density as high as $N_{HI} \sim 3.4 \times 10^{21}$ cm$^{-2}$ within a circular aperture of...
Figure 2. CMDs for the stars resolved in the outskirts of CL 77 and in two regions (T1 and T2) outlined to include the blue stars in the tails. Top left: spatial distribution of the stars in a (60 × 60) arcsec$^2$ field containing regions C, T1, and T2. Top right: CMD of CL 77 (big red points) superimposed on the CMD of the stars resolved in region (5;4) of A08 (small dots). An insertion shows the color distributions of the cluster and field stars down to 2 mag below the RGB tip. Middle and bottom panels: CMDs of T1 and T2, with superimposed Padova (Girardi et al. 2010) isochrones for log(age) = 6.75, 7.00, 7.25,...,7.75, 9.20, 9.50, and 10.00. Isochrones older than 1 Gyr are plotted using the red solid line up to the RGB tip phase, and the red dashed line for later phases. Labels indicate ages in Myr.

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

∼10 arcsec radius centered on the H$\alpha$ peak. It is also interesting that the infrared and H$\alpha$ emissions associated with T1 appear as part of a much longer stream wrapping around the galaxy from west to north. The H$\alpha$ stream appears to follow the rotation of the more external H$\alpha$ disk which counter-rotates with respect to the internal H$\alpha$ disk (Figure 14 in Hunter et al. 1999).

4. SUMMARY AND DISCUSSION

A11 showed that CL 77 is ∼7 Gyr old, massive ($M \sim 1.7 \times 10^6 M_\odot$), compact ($r_e \sim 1.9$ pc), and flattened ($\epsilon \sim 0.24$). Two other GCs in NGC 4449 are as massive and elliptical as CL 77 (CL 34 and CL 79 in A11), with fairly similar CMDs and color distribution of their RGB stars. CL 77 is however peculiar because it is located at the projected center of a symmetric structure outlined by blue stars reminiscent of tidal tails. CL 77 is the only GC in NGC 4449 that appears associated with such a structure. The presence of blue tails is also unusual because the cluster is located far away from the galaxy center (∼3 kpc) and from any region of active SF. Moreover, in a diagram of mean projected mass density inside $r_e$ versus total mass (Figure 3 in Walcher et al. 2005), it lies at the upper end of the GC distribution, where galaxy nuclei are. Hence, a possible interpretation is that CL 77 is what remains of a dwarf galaxy being disrupted by NGC 4449, similarly to what is suggested for ω Cen and G1 (e.g., Bekki & Freeman 2003; Meylan et al. 2001).

The stars resolved in the outskirts of the cluster confirm that it is old and indicate that its metallicity is consistent with ∼1/4 solar, i.e., similar to that of NGC 4449. The blue tails host recent SF: T2, closer to the galaxy body, exhibits an SF episode between ∼200 and ∼50 Myr ago; T1 hosts younger
SF than in T2, occurred until $\sim$20 Myr ago, and possibly still active as indicated by the presence of ionized gas (Hunter & Gallagher 1990). T1 is also associated with PAH and dust emission, and with one of the brightest H I spots in the galaxy ($N_{\text{HI}} \sim 3.4 \times 10^{21} \text{ cm}^{-2}$). This emission appears as part of a much longer stream which wraps around the galaxy, and which counter-rotates with respect to the inner H I disk.

The presence of recent SF in the tails suggests that supposed accreted galaxy had plenty of gas; thus, it probably was a dwarf irregular, a small late-type spiral, or a H I-rich dwarf elliptical (dE), like, e.g., those discovered in the Virgo cluster by Conselice et al. (2003). Furthermore, T1 is associated with one of the brightest H I spots in NGC 4449, which may be gas belonging to the accreted galaxy. Another possibility is that this gas was already present in NGC 4449; however, its high density suggests that compression may have occurred, and this requires interaction with another gas-rich system.

Rossa et al. (2006) showed that, for spiral galaxies, the mass of the central nuclear star cluster correlates with the mass/luminosity of the bulge, and the same result was found by Wehner & Harris (2006) for dE galaxies. The correlation is such that $\log M_{\text{cluster}} = (1.04 \pm 0.06) \times \log M_{\text{bulge}} - (3.10 \pm 0.60)$. From $M_{\text{CL77}} \sim 1.7 \times 10^6 M_\odot$, we derive that the parent galaxy bulge or spheroid had a mass of $\sim 0.93^{+3.4}_{-0.73} \times 10^9 M_\odot$. This is the total mass, from both luminous and dark matter, contained within the central spheroidal component of the galaxy, and it is largely dominated by the luminous mass. If the galaxy was a spiral with substantial disk, then the total galaxy mass may have been even larger. Comparing this value with NGC 4449’s total stellar mass of $\sim 3 \times 10^9 M_\odot$, as derived from the SF history in McQuinn et al. (2010), we obtain a mass ratio of $\sim 3:1$ (but note that the large scatter in the Wehner & Harris 2006 relation implies mass ratios in the range of 15:1–0:7:1, considering the 1σ error in the satellite mass). For comparison, typical (visible) masses often quoted for the LMC and SMC are $\sim 2 \times 10^{10} M_\odot$ and $\sim 2 \times 10^9 M_\odot$, respectively (see, e.g., Besla et al. 2007, Section 5.1) resulting in an LMC:SMC ratio of 10:1.

Admittedly, from the available data, we cannot prove that T1 and T2 are physically associated with CL 77, and the possibility that we are seeing the chance superposition along the line of sight of SF regions with a cluster associated with the old spheroid of NGC 4449, although unlikely, cannot be ruled out. In the following we discuss some of the possible questions.

Why is there no evidence in our images for streams or tails of old stars associated with CL 77? Indeed, this appears as a
problem for our proposed scenario, since if the progenitor had a stellar mass of \( \sim 10^7 M_\odot \), the satellite remnant should have a surface brightness \( \mu_I \lesssim 22 \text{ mag arcsec}^{-2} \) (obtained in the assumption that the satellite stars are uniformly distributed over our ACS FOV). Since in the proximity of CL 77, \( \sim 3 \text{ kpc} \) away from the galaxy center, we measure \( \mu_I \sim 23 \text{ mag arcsec}^{-2} \) (but significantly brighter in the regions of the blue tails due to the contribution from young luminous stars), we should be able to detect streams associated with the disrupted galaxy. However, this problem may be solved considering the large scatter in the Weinher & Harris (2006) relation and the factor of \( \sim 5 \) uncertainty in the progenitor mass. For instance, if the satellite mass was as low as \( 2 \times 10^8 M_\odot \), its remnants would be probably too faint to be detected against the NGC 4449 background. Interestingly, a stellar stream was recently discovered in NGC 4449 (D. Martinez-Delgado et al. 2012, in preparation), but that stream is located on the opposite side of the galaxy from CL 77.

The blue tails extend \( \sim 50' \) in width, corresponding to \( \sim 1 \text{ kpc} \) at NGC 4449’s distance. Could the stripped debris spread so rapidly to occupy such a large width if it were originally more compact? N-body simulations show that, just after the satellite orbital pericenter, tidal tails are highly diffuse (see, e.g., Figure 4 in Klymewitski et al. 2009). Given the small (projected) distance of CL 77 from NGC 4449’s center, this possibility cannot be ruled out. Another possibility is that the accreted satellite was a very low surface brightness disk galaxy (like, e.g., Maffei I), with a lot of gas. The blue tails could be the result of SF resulting from gas compression in the interaction (not “traditional” tidal tails in the sense of material stripped off the tidal radius of the progenitor).

How might the outer regions of CL 77’s progenitor be completely stripped off over a long interaction history but fail to strip the gaseous component until recently? A possible answer comes from simulations of gas-rich dwarf galaxy satellites orbiting within an MW-sized halo accounting for the combined effects of tides and ram pressure stripping caused by a hot diffuse gaseous corona surrounding the MW (e.g., Mayer et al. 2006). They show that dwarfs with dark halos more massive than \( \sim 10^9 M_\odot \) lose most of their gas only if a heating source (e.g., the cosmic ultraviolet background at \( z > 2 \)) keeps the gas extended. Galaxies falling into the MW halo at lower redshift can retain significant amounts of the centrally concentrated gas.

To summarize, we consider the following properties as indications that CL 77 may be the nucleus of a former gas-rich satellite galaxy undergoing disruption by NGC 4449: (1) the cluster is associated with two tidal tails of young (age \( \lesssim 200 \text{ Myr} \)) stars; (2) in a diagram of mean projected mass density inside \( r_c \) versus total mass it occupies the locus of galaxy nuclei; and (3) one of the tails is associated with a concentration of H I and infrared (dust/PAHs) emission which appears as part of a much longer stream wrapping around the galaxy. In addition, CL 77 is highly massive and elliptical. Its mass is not too far from the values derived in the literature for \( \omega \text{ Cen} \) (2.5 \( \pm 0.3 \) \( \times 10^6 M_\odot \); van de Ven et al. 2006), and its ellipticity is comparable to those of \( \omega \text{ Cen} \) and G1 (\( \epsilon \sim 0.2 \); Pancino et al. 2000; Meylan et al. 2001). Kinematical data (for CL 77, for other clusters in NGC 4449, and possibly for some bright blue stars in the tails) or deeper imaging would be useful to further test the scenario in which CL 77 is the nucleus of an accreted galaxy.

CL 77 is of interest in that it may show the process of satellite disruption in a different phase than other known GCs suspected to be former galactic nuclei. It has been suggested (Bellazzini et al. 2008; Carretta et al. 2010) that \( \omega \text{ Cen} \) and M54 might have followed a similar evolutionary path, with M54 seen in an earlier phase compared to \( \omega \text{ Cen} \). CL 77 may represent an intermediate stage between M54, where the galaxy stream is still visible, and \( \omega \text{ Cen} \) or G1, where the presumed disrupted galaxy is no longer visible. By putting the various clusters in sequence we can create a times series of events composed of single-epoch “snapshots.” M54 is still surrounded by a parent galaxy that can be recognized as such (the Sgr dSph), but which is being drawn out into extended streams. CL 77 does not show a surrounding parent galaxy anymore, but it has surrounding features that hint at its former presence (the blue tails) as well as its association with an extended (H I and infrared) stream. Palomar 14 shows neither a surrounding parent galaxy nor an extended stream anymore, but short tails in the immediate vicinity of the cluster’s tidal radius are still evident. And finally, \( \omega \text{ Cen} \) and G1 show neither a surrounding parent galaxy, nor extended streams, nor local tails. In \( \omega \text{ Cen} \), only the presence of multiple stellar populations may still point to its former location at a galaxy center.

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REFERENCES

Annibali, F., Aloisi, A., Mack, J., et al. 2008, AJ, 135, 1900 (A08)
Annibali, F., Tosi, M., Aloisi, A., & van der Marel, R. P. 2011, AJ, 142, 129 (A11)
Bekki, K., & Freeman, K. C. 2003, MNRAS, 346, L11
Bellazzini, M., Ibata, R. A., Chapman, S. C., et al. 2008, AJ, 136, 1147
Bellini, A., Bedin, L. R., Piotto, G., et al. 2010, AJ, 140, 631
Besla, G., Kallivayalil, N., Hernquist, L., et al. 2007, ApJ, 668, 949
Carretta, E., Bragaglia, A., Gratton, R. G., et al. 2010, ApJ, 714, L7
Conselice, C. J., O’Neil, K., Gallagher, J. S., & Wyse, R. F. G. 2003, ApJ, 591, 167
Dale, D. A., Cohen, S. A., Johnson, L. C., et al. 2009, ApJ, 703, 517
Dinescu, D. I., van Altena, W. F., Girard, T. M., & López, C. E. 1999, AJ, 117, 277
Djorgovski, S. G., Gal, R. R., McCarthy, J. K., et al. 1997, ApJ, 474, L19
Ferguson, A. M. N., Irwin, M. J., Ibata, R. A., Lewis, G. F., & Tanvir, N. R. 2002, AJ, 124, 1452
Gebhardt, K., Rich, R. M., & Ho, L. C. 2002, ApJ, 578, L41
Girardi, L., Williams, B. F., Gilbert, K. M., et al. 2010, ApJ, 724, 1030
Helm, A., & White, S. D. M. 1999, MNRAS, 307, 495
Hunter, D. A., & Gallagher, J. S., III. 1990, ApJ, 362, 480
Hunter, D. A., Rubin, V. C., Swaters, R. A., Sparke, L. S., & Levine, S. E. 2005, ApJ, 634, 281
Hunter, D. A., van Woerden, H., & Gallagher, J. S. 1999, AJ, 118, 2184
Ibata, R., Irwin, M., Lewis, G., Ferguson, A. M. N., & Tanvir, N. 2001b, Nature, 412, 49
Ibata, R., Irwin, M., Lewis, G. F., & Stolte, A. 2001a, ApJ, 547, L133
Ibata, R. A., Gilmore, G., & Irwin, M. J. 1994, Nature, 370, 194
Johnson, C. I., & Pilachowski, C. A. 2010, ApJ, 722, 1373
Johnston, K. V., Hernquist, L., & Bolte, M. 1996, ApJ, 465, 278
Klimewitki, J., Lokas, E. L., Kazantzidzis, S., et al. 2009, MNRAS, 400, 2162
Lee, J. C., Kennicutt, R. C., Funes, J. G., et al. 2004, BAAS, 36, 1442
Majewski, S. R., Skrutskie, M. F., Weinberg, M. D., & Ostheimer, J. C. 2003, ApJ, 599, 1082
Mayer, L., Mastropietro, C., Wadsley, J., Stadel, J., & Moore, B. 2006, MNRAS, 369, 1021
McQuinn, K. B. W., Skillman, E. D., Cannon, J. M., et al. 2010, ApJ, 721, 297
Meylan, G., Sarajedini, A., Jablonka, P., et al. 2001, AJ, 122, 830
Pancino, E., Ferraro, F. R., Bellazzini, M., Piotto, G., & Zoccali, M. 2000, ApJ, 534, L83
Rossa, J., van der Marel, R. P., Böker, T., et al. 2006, AJ, 132, 1074
Siegel, M. H., Majewski, S. R., Law, D. R., et al. 2011, ApJ, 743, 20
Sollima, A., Bellazzini, M., Smart, R. L., et al. 2009, MNRAS, 396, 2183
Sollima, A., Martínez-Delgado, D., Valls-Gabaud, D., & Peñarrubia, J. 2011, ApJ, 726, 47
van der Marel, R. P., Rossa, J., Walcher, C. J., et al. 2007, in IAU Symp. 241, Stellar Populations as Building Blocks of Galaxies, ed. A. Vázdekis & R. F. Peletier (Cambridge: Cambridge Univ. Press), 475
van de Ven, G., van den Bosch, R. C. E., Verolme, E. K., & de Zeeuw, P. T. 2006, A&A, 445, 513
Walcher, C. J., van der Marel, R. P., McLaughlin, D., et al. 2005, ApJ, 618, 237
Walter, F., Brinks, E., de Blok, W. J. G., et al. 2008, AJ, 136, 2563
Wehner, E. H., & Harris, W. E. 2006, ApJ, 644, L17