Cume: #414

Passing grade for the cume is 70 points

This paper discussed the discovery of a globular cluster inside a dwarf galaxy DDO216. The globular cluster has mass $m = 10^5 M_\odot$, and it is very close but not exactly at the galaxy center ($\sim$ 30pc). How can we explain this situation? If the cluster was formed at that position, why the tidal forces did not destroy it? If it formed away from the center, how did it come so close to it at present?

While accurate predictions for the position of the cluster require detailed modeling of the mass profile of DDO216 and of the cluster, we can make estimates using a number of simplifying, but reasonable assumptions. Using the following information, you are asked to address two problems: (1) how large is the expected effect of the tidal stripping in the case of the globular cluster in DDO216, and (2) is the dynamical friction strong enough to bring the cluster close to the center?

Here are parameters and approximations for the galaxy and the cluster:

(1) The galaxy has a circular velocity of v_c = 20km/s. It is a transitional dwarf with a significant mass in stars and gas. This typically leads to a flat circular velocity curve $v_c(R) \approx$ const, which we assume to be true all the way to the center of the galaxy. We also assume that the distribution of mass is nearly spherical. This is sufficient to estimate the mass $M(R)$ and density $\rho(R)$ of the galaxy at any radius R.

(2) The cluster has mass $m = 10^5 M_\odot$ and half-mass radius r_h = 13pc. We can assume that most of its mass is within $2r_h$.

parsec $=3.08 \times 10^{18}$cm $\quad M_\odot = 2 \times 10^{33}$g $\quad G = 6.67 \cdot 10^{-8}$cm^{3}sec^{-2}g^{-1} $\quad$ 1 year=3600*24*365 secs

1. **50pt** Estimate the tidal radius of the cluster at different distances from the center of the galaxy.

   (a) **10pt** Find mass of the galaxy $M(R)$ and its density $\rho(R)$[1].
   Answer: We find mass using the fact that the circular velocity is constant:

$$\frac{GM(R)}{R^2} = \frac{v_c^2}{R} \Rightarrow M(R) = \frac{Rv_c^2}{G} \tag{1}$$

$$M(R) = 230\left(\frac{R}{pc}\right)\left(\frac{v_c}{km/s}\right)^2 M_\odot = 9 \times 10^4 \left(\frac{R}{pc}\right) M_\odot. \tag{2}$$

Density:

$$M(R) = 4\pi\int_0^R R^2\rho(R)dR = \frac{RV_c^2}{G} \propto R \quad \Rightarrow \rho = AR^{-2} \quad A = \frac{v_c^2}{4\pi G}. \tag{3}$$

[1]Just in case, $\rho \neq M/V$

(b) **20pt** Derive an expression for the tidal radius by equating the tidal force at the galactocentric distance R to the force of gravity of the cluster at distance r from the cluster center.

Answer: Tidal force $g_{\rm tide}(R,r)$ at a distance R from the galaxy center and distance r from the cluster center along the radial direction is

$$g_{\rm tide}(R,r) = \frac{dg}{dR}\Delta R = -\frac{2GM(R)r}{R^3}. \tag{4}$$

Note that here to make the calculations simpler we neglected the derivative of the mass $M(R)$ with radius. Now we estimate the tidal radius $r_{\rm tide}$ and tidal mass $m_{\rm tide}$ of the satellite by equating forces:

$$\frac{Gm_{\rm tide}}{r^2_{\rm tide}} = \frac{2GM(R)r_{\rm tide}}{R^3} \quad \Rightarrow r_{\rm tide} = R\left[\frac{m_{\rm tide}}{2M(R)}\right]^{1/3} \tag{5}$$

(c) **20pt** Estimate the tidal radius at (a) $R = 100$pc and (b) $R = 1000$pc. How does it compare to the radius of the cluster? How important is the tidal stripping for the cluster at these two radii? When estimating the force of gravity due to the cluster, we use the total mass of the cluster m. This is a good approximation, if the tidal radius is larger or comparable to the size of the cluster. After we make the estimates, we check whether the approximation is accurate.

Answer: We find:

$$r_{\rm tide}(\text{kpc}) = 1\,\text{kpc}\left(\frac{10^5}{2\cdot 9\times 10^7}\right)^{1/3} = 82\text{ pc}, \tag{6}$$

$$r_{\rm tide}(100\text{pc}) = 100\,\text{pc}\left(\frac{10^5}{2\cdot 9\times 10^6}\right)^{1/3} = 18\text{ pc}, \tag{7}$$

These estimates confirm conclusions of the paper that the cluster should have been formed at relatively large distance from the galaxy center ~ 1 kpc because the tidal forces seem to be quite important at $R < 100$pc and may have substantially reduced its mass (if not totally destroyed). However, at these small distances our approximation that the density increases as $\rho \propto R^{-2}$ may become questionable.

2. **50pt** Estimate the dynamical friction time-scale for the cluster at different initial radii. Below you can find the formula of the dynamical friction. You will need it to estimate the friction time-scale $t_{\rm fric} \approx V_s/(dV_s/dt)$.

   (a) **10pt** What is the mechanism of the dynamical friction? What object is experiencing the friction and who is providing the "friction"?

   Answer: Dynamical friction is experienced by a massive object moving in a field of smaller objectes. The gravitational force of the massive object deflects orbits of field *particles, which creates an overdensity of mass behind the massive object. In turn, this generates the force of gravity that slows the motion of the massive object. Thus, it is the field particles that are responsible for the dynamical friction.*

(b) **5pt** What is the Coulomb logarithm?

Answer: The Coulomb logarithm $\ln(\Lambda)$ *is the term that comes from the integration of effects of collisions with field particles at different impact parameters (distances) from the massive object. Parameter* Λ *is the ratio of* b_{max} *the largest impact parameter (typically the size of the system) and the smallest impact parameter* b_{min} *corresponding the deflection angle of 90 degrees.*

(c) **5pt** Why there is a factor $f(v_* < V_s)$ – the fraction of particles moving with velocities less than the satellite velocity?

Answer: The asymmetry of the mass distribution around the massive object is the key for the dynamical friction. Without the asymmetry there is no dynamical friction. Only the particles that move slower than the massive object create the asymmetry.

(d) **5pt** The satellite loses energy and angular momentum when it spirals around the galaxy and gradually gets closer to the center. Where do the energy and angular momentum go to?

Answer: The energy and angular momentum go into the field particles. They gain energy and angular momentum when the satellite spirals into the center.

(e) **25pt** Estimate the dynamical friction time for a satellite starting at (a) 1 kpc and (b) 10 kpc. Assume that the satellite moves with the circular velocity. Is there enough time for the satellite to get as close to the center as observed? (Present answers in years).

Answer: We start with writing the expression for the friction time:

$$t_{\rm df} \equiv V_s/(dV_s/dt) = \frac{V_s^3}{4\pi G^2 M_s \rho \log(\Lambda) f(v_* < V_s)}, \tag{8}$$

Now use the density $\rho(R) = v_c^2/4\pi G R^2$ *for the galaxy and assume that the satellite moves with the circular velocity:*

$$t_{\rm df} = \frac{r^2 V_c}{G M_s \log(\Lambda) f(v_* < V_s)}, \tag{9}$$

Estimate $t_{\rm df}$ *at different initial radii:*

$$t_{\rm df} = 9 \times 10^3 \left[\frac{R}{\rm pc}\right]^2 \text{ years} \tag{10}$$

$t_{\rm df}(1\ {\rm kpc}) = 9 \times 10^9$ years *and* $t_{\rm df}(10\ {\rm kpc}) = 9 \times 10^{11}$ years. *Because the age of the Universe is* $t_U = 13 \times 10^9$ *years, the conclusion is clear: there is barely enough time to move from 1 kpc distance, but not from larger distances.*

Dynamical friction is given by the following equation:

$$\frac{d\vec{V}_s}{dt} = -4\pi G^2 M_s \rho \log(\Lambda) f(v_* < V_s) \frac{\vec{V}_s}{V_s^3}, \tag{11}$$

where ρ is the density of the matter around a satellite with mass M_s moving with velocity $\vec{V}_s$. The Coulomb logarithm $\log(\Lambda) \approx 10$. The fraction of particles moving with velocities less than the satellite velocity $f(v_* < V_s) \approx 0.5$.

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DDO 216-A1: A Central Globular Cluster in a Low-luminosity Transition-type Galaxy*

Andrew A. Cole[1], Daniel R. Weisz[2], Evan D. Skillman[3], Ryan Leaman[4], Benjamin F. Williams[5], Andrew E. Dolphin[6], L. Clifton Johnson[7], Alan W. McConnachie[8], Michael Boylan-Kolchin[9], Julianne Dalcanton[5], Fabio Governato[5], Piero Madau[10], Sijing Shen[11], and Mark Vogelsberger[12]

[1] School of Physical Sciences, University of Tasmania, Private Bag 37, Hobart, Tasmania, 7001 Australia; andrew.cole@utas.edu.au
[2] Department of Astronomy, University of California, Berkeley, Berkeley, CA 94720, USA
[3] Minnesota Institute for Astrophysics, University of Minnesota, Minneapolis, MN 55441, USA; skillman@astro.umn.edu
[4] Max-Planck Institut für Astronomie, Königstuhl 17, D-69117, Heidelberg, Germany
[5] Department of Astronomy, University of Washington, Box 351580, Seattle, WA 98195, USA
[6] Raytheon; 1151 E. Hermans Road, Tucson, AZ 85756, USA; adolphin@raytheon.com
[7] Center for Astrophysics and Space Sciences, University of California, San Diego, 9500 Gilman Drive, La Jolla, CA 92093, USA
[8] National Research Council, Herzberg Institute of Astrophysics, 5071 West Saanich Road, Victoria, BC V9E 2E7, Canada; alan.mcconnachie@nrc-cnrc.gc.ca
[9] Department of Astronomy, The University of Texas at Austin, 2515 Speedway, Stop C1400, Austin, TX 78712-1205, USA
[10] Department of Astronomy and Astrophysics, University of California, 1156 High Street, Santa Cruz, CA 95064, USA
[11] Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge, CB3 0HA, UK
[12] Department of Physics, Kavli Institute for Astrophysics and Space Research, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

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Abstract

We confirm that the object DDO 216-A1 is a substantial globular cluster at the center of Local Group galaxy DDO 216 (the Pegasus dwarf irregular), using *Hubble Space Telescope* ACS imaging. By fitting isochrones, we find the cluster metallicity $[M/H] = -1.6 \pm 0.2$, for reddening $E(B-V) = 0.16 \pm 0.02$; the best-fit age is 12.3 ± 0.8 Gyr. There are $\approx$30 RR Lyrae variables in the cluster; the magnitude of the fundamental mode pulsators gives a distance modulus of 24.77 ± 0.08—identical to the host galaxy. The ratio of overtone to fundamental mode variables and their mean periods make DDO 216-A1 an Oosterhoff Type I cluster. We find a central surface brightness of 20.85 ± 0.17 F814W mag arcsec^{-2}, a half-light radius of $3\farcs1$ (13.4 pc), and an absolute magnitude M814 $= -7.90 \pm 0.16$ ($M/M_\odot \approx 10^5$). King models fit to the cluster give the core radius and concentration index, $r_c = 2\farcs1 \pm 0\farcs9$ and $c = 1.24 \pm 0.39$. The cluster is an "extended" cluster somewhat typical of some dwarf galaxies and the outer halo of the Milky Way. The cluster is projected $\lesssim$30 pc south of the center of DDO 216, unusually central compared to most dwarf galaxy globular clusters. Analytical models of dynamical friction and tidal destruction suggest that it probably formed at a larger distance, up to $\sim$1 kpc, and migrated inward. DDO 216 has an unexceptional specific cluster frequency, $S_N = 10$. DDO 216 is the lowest-luminosity Local Group galaxy to host a $10^5\ M_\odot$ globular cluster and the only transition-type (dSph/dIrr) galaxy in the Local Group with a globular cluster.

Key words: galaxies: dwarf – galaxies: individual (DDO 216) – galaxies: star clusters: general – Local Group

Supporting material: machine-readable table

1. Introduction

Dwarf galaxies ($M_* \lesssim 10^8 M_\odot$) are the most abundant class of galaxies in the universe. They occupy an important part of parameter space for understanding the feedback processes that seem to govern the relationships between dark halo mass, baryon fraction, and star formation efficiency. Furthermore, their progenitors at high redshift may have played an important role in reionizing the universe (Robertson et al. 2013). Despite the ubiquity of dwarf galaxies, it is challenging to reliably measure their physical properties and put them in their appropriate cosmological context (e.g., Boylan-Kolchin et al. 2015).

Most dwarf galaxies are undetectable beyond redshift $z \approx$ 1–2, even in the Hubble Ultra Deep Field or with planned *James Webb Space Telescope* observations (Boylan-Kolchin et al. 2016). Thus, observations of Local Group galaxies have set the benchmark for the accuracy and precision with which ancient star formation rates (SFRs) and chemical evolution histories can be measured (e.g., Cole et al. 2014; Skillman et al. 2014; Weisz et al. 2014b, and references therein). Long-lived main-sequence (MS) stars born at lookback times $\geqslant$10 Gyr, corresponding to $z \gtrsim 2$, are a direct probe of galaxy evolution in the universe from the earliest star-forming period through the epoch of reionization and its aftermath.

In this paper we present a photometric analysis of the understudied star cluster at the center of DDO 216 (the Pegasus dwarf irregular [PegDIG], UGC 12613), which we observed serendipitously during our *Hubble Space Telescope* (*HST*) program to measure the complete star formation history (SFH) of this galaxy. PegDIG ($M_V = -12.5 \pm 0.2$) is roughly a magnitude fainter than the Fornax and Sagittarius dwarfs, which makes it one of the least luminous galaxies known to host a cluster near the peak of the globular cluster luminosity function (see da Costa et al. 2009; Georgiev et al. 2009b, for examples of similar clusters in dwarfs with $M_V \approx -11.5$).

First, we review the basic parameters of the galaxy, and then we describe our observations and reductions in Section 2. Our

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analysis of the structure and content of the star cluster DDO 216-A1, including age and metallicity estimates based on the color–magnitude diagram (CMD) and an analysis of the variable star population of the cluster, is given in Section 3. We place DDO 216-A1 in context with the population of massive star clusters in dwarf galaxies and summarize our results in Section 4.

1.1. Globular Clusters in Dwarf Galaxies

Given deep enough observations, it is relatively straightforward to derive SFRs at high lookback times for galaxies within the Local Group. It is more difficult to identify the triggers of star formation. For example, a majority of dwarf–dwarf major mergers are expected to have occurred in the first few billion years after galaxy formation began (e.g., Deason et al. 2014), but because of the destructive nature of mergers, most of the obvious evidence for merger activity will have long since vanished.

Globular clusters are an important window into this process because they require extreme conditions to form, suggestive of vigorous star formation in the mode often associated with galaxy mergers and interactions (e.g., Brodie & Strader 2006, and references therein). Globular clusters are tightly bound and will typically survive for a Hubble time unless disrupted in a hostile tidal environment, but the relatively shallow potential wells of dwarf galaxies are not generally conducive to cluster disruption.

As a result, many globular and open clusters are known in dwarf galaxies in the Local Group and beyond, in enough numbers to make statistical associations between properties like host galaxy morphology and cluster colors and sizes (e.g., Sharina et al. 2005; Miller & Lotz 2007). These span a range of sizes from extremely luminous and dense nuclear star clusters to low-mass open cluster or association analogs, in galaxies down to some of the least luminous known.

In the Local Group, recent work has discovered examples of modest star clusters even among the smallest galaxies (e.g., Crnojević et al. 2016) and more massive, sometimes extended clusters in some of the larger irregular galaxies (Sharina et al. 2007; Hwang et al. 2011). In light of these discoveries and others, Zaritsky et al. (2016) have suggested that some of the outer halo globular clusters thought to be Galactic globular clusters may in fact be hosted by undiscovered low surface brightness galaxies. However, the lowest-luminosity Local Group galaxies with cataloged globular clusters similar to the massive and dense globulars of the Milky Way are Fornax and Sagittarius ($M_V = -13.4$ and $\lesssim -13.5$, respectively).

1.2. The Pegasus Dwarf Irregular, DDO 216

The Pegasus dwarf irregular galaxy, PegDIG, was discovered by A.G. Wilson in the early 1950s on Palomar Schmidt plates (Holmberg 1958). From early on it was considered to be a candidate member of the Local Group with a distance of $\sim$1 Mpc. The case for membership was supported by the negative heliocentric H I radial velocity found by Fisher & Tully (1975). PegDIG is considered a distant M31 satellite ($d_{\rm M31} \approx 470$ kpc; McConnachie et al. 2007); it has not been proven that it has ever interacted with M31, although it is more likely than not that PegDIG has previously been within M31's virial radius (Shaya & Tully 2013; Garrison-Kimmel et al. 2014). PegDIG is fairly isolated at the present time, its nearest neighbor being the M31 satellite And VI, just over 200 kpc away. It is quite unlikely that PegDIG has had strong tidal interactions with any other known galaxy during the past several gigayears.

PegDIG is a fairly typical small irregular galaxy, with roughly 1:1 gas-to-stellar mass ratio, although it has virtually no current star formation as measured by Hα emission (Young et al. 2003). This leads to its classification as a transition-type dwarf, with properties intermediate between the dwarf spheroidal (dSph) and dwarf irregular (dIrr) types (McConnachie 2012). It has an ordinary metallicity of [Fe/H] $\approx -1.4 \pm 0.3$ for its stellar mass of $\approx 10^7\ M_\odot$ (Kirby et al. 2013). Unlike the spheroidal galaxies, it appears to be rotating; both H I (Kniazev et al. 2009) and stellar (Kirby et al. 2014) data suggest a rotation speed (not corrected for inclination) of $\approx$15–20 km s^{-1}. McConnachie et al. (2007) drew attention to the cometary appearance of the neutral gas and attributed the asymmetric morphology to ram pressure stripping by diffuse gas in the Local Group, although this conclusion is disputed, based on much deeper H I observations, by Kniazev et al. (2009).

The SFH of PegDIG has been estimated from ground-based data reaching a limiting absolute magnitude of $M_I \approx -2.5$ (Aparicio et al. 1997), and from *HST*/WFPC2 observations (Gallagher et al. 1998) reaching $\approx$2.5 mag deeper. Within large uncertainties (Weisz et al. 2014a), the picture that emerges from these studies is of star formation that has spanned a Hubble time, likely to be declining over time following an early epoch of high SFR. The SFR has certainly declined with time over the past $\approx$1–2 Gyr, despite the large reservoir of neutral gas.

In its extended SFH, PegDIG appears to have more in common with the dIrr galaxies than with a typical dSph, consistent with its retention of neutral gas to the present day and with the assertion of Skillman et al. (2003a) that transition-type galaxies represent the low-mass/low-SFR end of the dwarf irregular population (see also Weisz et al. 2011). The precise SFH over the full lifetime of the galaxy will be determined in a future paper in this series (A. Cole et al. 2017, in preparation).

2. Observations and Data Reduction

We observed PegDIG using the Advanced Camera for Surveys Wide Field Camera (ACS/WFC) as part of the Cycle 22 program GO-13768. The observations, which comprise 34.3 and 37.4 ks in the F814W (Broad *I* band) and F475W (Sloan *g* band) filters, respectively, were made between 2015 July 23 and 26. A total of 29 orbits were allocated to the Pegasus observations, split into 15 visits of one to two orbits each to facilitate the detection of short-period variable stars. Each orbit was broken into one exposure in each filter. Parallel observations at a distance of $\approx 6'$ were obtained simultaneously through the equivalent filters on the Wide Field Camera 3.

The charge-transfer-efficiency-corrected images were processed through the standard *HST* pipeline, and photometry was done using the most recent version of DOLPHOT, with its *HST*/ACS-specific modules (Dolphin 2000). Extended objects and residual hot pixels were rejected based on their brightness profiles, and aperture corrections were derived based on relatively isolated stars picked from around the image. Stars that were found to suffer from excessive crowding noise (crowding parameter >1.0) owing to partially resolved bright synthesis models by Bruzual & Charlot (2003). Using their preferred initial mass function (Chabrier 2003), they found a mean model $M/L \approx 1.9$ for the old clusters. The median dynamical mass-to-light ratio for the clusters in their sample was 82% ± 7% of this value, with a substantial scatter.

Our absolute magnitude for DDO 216-A1 is $M_V = -7.14 \pm 0.16$, which translates to a V-band luminosity of $(5.97 \pm 0.95) \times 10^4\ L_\odot$. Using the M/L estimates from McLaughlin & van der Marel (2005) gives either 1.13 ± 0.18 (population synthesis) or 0.93 ± 0.15 (dynamical) $\times 10^5\ M_\odot$. The true range of possible values is even larger, because of potential variations in the initial mass function and the observed variations between clusters. Given the lack of kinematic constraints, an appropriate way to express the probable mass of the cluster is $\log(M/M_\odot) = 5.0 \pm 0.1$. This is entirely consistent with mass estimates for similarly bright and extended, old clusters in the Milky Way (e.g., IC 4499; Hankey & Cole 2011) and the LMC (e.g., Reticulum; Suntzeff et al. 1992).

4.3. Formation, Migration, and Survival

The cluster's projected position near the center of PegDIG raises the question of its provenance and survival. If the cluster formed in situ at the center of the galaxy, then it is natural to ask how it has survived tidal evaporation for 12 Gyr. Alternatively, if DDO 216-A1 formed at an arbitrary location in the galaxy, then dynamical friction must be acting efficiently enough to bring it nearly to the center within its lifetime.

Survivability of clusters in dwarf galaxies can be calculated probabilistically using analytical models for dynamical friction and cluster evolution (R. Leaman et al. 2017, in preparation). Using the dynamical friction formula from Petts et al. (2016), a range of galaxy mass profiles and cluster orbits can be tested to see whether there are any plausible initial conditions conducive to cluster inspiral and survival. The half-light radius of PegDIG is ≈700 pc (Kirby et al. 2014), and its stellar mass is $\log(M_*) \approx 10^7\ M_\odot$ (McConnachie 2012), but its mass profile is not extremely well known. To a first approximation it could be taken as similar to a scaled-down version of WLM, which is well fit by a Navarro et al. (1997) profile with virial mass $M_{\rm vir} = 10^{10}\ M_\odot$ and concentration parameter $c = 15$ (Leaman et al. 2012).

To reflect the uncertainties in the parameters, we ran 2000 trials in which the important unconstrained parameters were drawn at random and the dynamical friction and tidal destruction timescales were calculated analytically. The parameters and their range of sampled values were the initial distance and orbital eccentricity for DDO 216-A1 (evenly distributed from 0 to 2 kpc and from 0 to 1, respectively) and the virial mass (lognormal distributed around $10^{10}\ M_\odot$), concentration index (normally distributed around $c = 12.5$), and Einasto profile slope (evenly distributed between 0 and 1) for the PegDIG halo.

In this set of trials, 27% of the clusters are found to have survival times longer than 12 Gyr and dynamical friction timescales shorter than this. Within the range of parameters considered, there were no strong trends of survivability in the concentration index, Einasto profile slope, or virial mass, but the best cluster survivability is found for birthplaces from ≈300 to 1000 pc from the galaxy center; nearly half of $10^5\ M_\odot$ clusters born within this range sink to within $\lesssim$100 pc of the center without tidal destruction over their lifetime. Clusters born interior to this region tend to be tidally disrupted, and clusters born in the galaxy outskirts have dynamical friction timescales longer than a Hubble time. The general feature of the analysis, that in many cases clusters will be disrupted, but that the most massive will sometimes survive to be observed near the center of the host galaxy, is consistent with advanced numerical simulations of star formation in dwarfs (C. Christensen 2017, private communication).

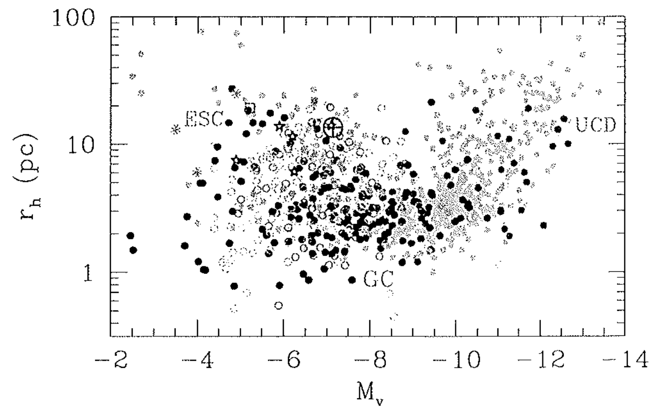

Figure 8. Half-light radius and absolute magnitude for a selection of stellar systems. Following Brodie et al. (2011), the regions of the (r_h, M_V) plane are labeled as follows: ESC—extended star clusters; UCD—ultracompact dwarfs and nuclei; GC—globular clusters. Purple circled cross: DDO 216-A1; gray circles: clusters and dwarf galaxies (Brodie et al. 2011); black circles: Milky Way globulars (Harris 1996, 2010 edition); red circles: clusters in early-type dwarfs. Filled circles denote galaxy nuclei and other clusters within 150 pc of the host center (Sharina et al. 2005; Côté et al. 2006; Georgiev et al. 2009b); cyan circles: clusters in late-type dwarfs, from the same sources. Filled and open symbols as above; orange asterisks: clusters in Local Group dwarfs fainter than PegDIG; blue stars: clusters in NGC 6822; green triangle: WLM cluster; pink filled square: Scl-dE1-GC1; light-blue open square: Reticulum; gold triangle: M54 (Sagittarius nucleus). See the text for references to individual objects.

Guillard et al. (2016) performed hydrodynamical simulations of a larger dwarf ($M_* = 10^{9.5}\ M_\odot$) and observed exactly this behavior, producing a $10^8\ M_\odot$ nuclear star cluster as the result of inspiral, gas accretion, and merging of an initially $10^4\ M_\odot$ protocluster formed in the outskirts of the dwarf. Their simulated cluster arrives in the central part of the dwarf after ≈1 Gyr and is quenched by a final merger with another large cluster. This raises the possibility that DDO 216-A1 might show an extended history of star formation as the result of dry or wet mergers, although there is little evidence for this in the current data.

These results show that the cluster location is consistent with formation across a large volume of PegDIG, excluding the central region where it is now observed. Given the propensity of clusters to dissolve when located at the center of the galaxy, it seems unlikely that DDO 216-A1 formed at its current location. Because dynamical friction tends to stall when the cluster reaches the radius at which the host galaxy density profile flattens into a core, it is not surprising that the cluster is not observed at the precise center of PegDIG. Both of these factors point to the likelihood that the true distance from the PegDIG center to the cluster is larger than the projected separation.

4.4. DDO 216-A1 in Context

Following Brodie et al. (2011), we show the half-light radius and absolute magnitude of a sample of stellar systems in