Butterfly in a Cocoon, Understanding the Origin and Morphology of Globular Cluster Streams: The Case of GD-1

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Abstract

Tidally disrupted globular cluster (GC) streams are usually observed, and therefore perceived, as narrow, linear, and one-dimensional structures in the 6D phase space. Here, we show that the GD-1 stellar stream, which is the tidal debris of a disrupted GC, possesses a secondary diffuse and extended stellar component (~100 pc wide) around it, detected at the >5σ confidence level. Similar morphological properties are seen in synthetic streams that are produced from star clusters that are formed within dark matter sub-halos and then accrete onto a massive host galaxy. This lends credence to the idea that the progenitor of the highly retrograde GD-1 stream was originally formed outside of the Milky Way in a now defunct dark satellite galaxy. We deem that in future studies, this newly found cocoon component may serve as a structural hallmark to distinguish between the in situ and ex situ (accreted) formed GC streams.

Key words: Galaxy: formation – Galaxy: halo – Galaxy: structure – globular clusters: general – stars: kinematics and dynamics

1. Introduction

It is generally believed that large galaxies, like the Milky Way, underwent an initial in situ formation phase that was followed by ex situ mass growth of the halo via merging and accretion of protogalactic fragments (Searle & Zinn 1978; Freeman & Bland-Hawthorn 2002). This suggests that today’s galaxies should contain contributions from both in situ and ex situ formed tracer components, such as globular clusters (GCs), depending on the galaxy’s assembly history. While for the Milky Way it is often assumed that the metal-rich GCs are associated with the in situ phase of galaxy formation, and that metal-poor GCs are all accreted (Forbes et al. 2018), this distinction is much harder to discern observationally, especially for the GC population in the stellar halo that shows a wide spread in metallicity (Carollo et al. 2007; Helmi 2008). However, this distinction is important to tightly constrain models of galaxy formation and evolution in a cosmological context. It is also relevant for dark matter studies, as accreted stellar objects tend to remain embodied within the dark envelope coming from the merging sub-halo progenitor; unlike stellar structures born within the Milky Way that are generally expected to be devoid of such dark sheaths.

The best examples of GCs that are a result of accretion in the Milky Way are currently provided by those that are associated with the Sagittarius dwarf galaxy (Bellazzini et al. 2003) and the LMC (Wagner-Kaiser et al. 2017). We know this as a certainty because we are witnessing the ongoing merging process of the parent satellites. However, the GCs and the baryonic content of the ancient accreted satellites that were deposited into our Galactic halo ≥5–6 Gyr ago do not specifically feature any characteristic observable clues conveying the history of their accretion. This is simply because such mergers have been gradually stripped of their dark matter envelopes and their observable stars have been mixed into the halo, leaving hardly any relics of their earlier existence. Therefore, one of the other approaches to distinguish accreted GCs is to instead survey the effects imprinted on their internal structure and kinematics (such as studying the evolution of their half-mass radii or measuring their velocity anisotropies), which depends on the strength of the underlying tidal field. The idea is that GCs born in the massive the Milky Way would be subjected to a different force field during their lifetime from the GCs that originated in dwarf galaxies and were later accreted. However, simulations show that post-accretion, the clusters adapt to the new tidal environment of their host galaxy, losing any signature of their original environment in a few relaxation times (Miholics et al. 2016; Bianchini et al. 2017).

Here we aim to examine if narrow stellar streams, which are remnants of GCs, can be useful in addressing this problem and potentially disentangling the two different types of GC/stellar populations present in the halo.

A GC that undergoes tidal disruption due to its interaction with a massive host forms a long and thin stellar stream. Typically, their physical widths are comparable to the tidal radii of GC systems (a few tens of parsecs), and are therefore often observed to be quite narrow, linear, and one-dimensional structures in the 6D phase space, devoid of any extended structural component. Here we revisit one of the GC streams of the Milky Way, the GD-1 stream (Grillmair & Dionatos 2006), and examine its structure to check if it possesses any morphological signature that can provide useful insights into the origin and the embryonic association of its progenitor system with an ancient satellite merger.

This paper is arranged as follows. In Section 2 we present our diagnoses of the GD-1 structure, where we discover a secondary extended and diffuse stellar component around the
thin stream at the >5σ confidence level. In Section 3 we show that the detected component is a genuine feature and not an artifact of underlying background contaminants. In order to interpret our findings, we further analyze a set of synthetic streams produced in cosmological simulations in Section 4, which ultimately assists us both in making a strong case for this detection and in understanding the origin of this secondary stream feature. We finally present our conclusion and discuss the prospects of our study in Section 5.

2. Diagnosing the GD-1 Stream

The GD-1 stellar stream is observed as a long (∼80°, Price-Whelan & Bonaca 2018) and exceptionally narrow structure in the sky (angular width of ∼0.5°), and was previously measured to have a physical width of ∼20 pc (Koposov et al. 2010). Its velocity dispersion in the direction tangential to the line of sight has been measured to be <2.3 km s⁻¹ (95% conf.), and it is an extremely metal-poor structure ([Fe/H] = −2.24 ± 0.21) (Malhan & Ibata 2019). The color–magnitude diagram of GD-1 is similar to that of the M13 GC (Grillmair & Dionatos 2006) and corresponds to a stellar population of age 10–12 Gyr. While the location of the progenitor of GD-1 is currently unknown (de Boer et al. 2018; Malhan et al. 2018a; Price-Whelan & Bonaca 2018; Webb & Bovy 2019), and indeed it may have been completely disrupted long ago, these stream properties strongly imply that GD-1 is the remnant of a GC.

We first detect the GD-1 stream structure of interest, using our STREAMFINDER algorithm (Ibata et al. 2018, 2019; Malhan & Ibata 2018; Malhan et al. 2018b). The required stellar stream density map was obtained from processing the Gaia DR2 data set, after adopting a Single Stellar population (SSP) template model of...
consistent with the on-sky extent of the GD-1 stream, and first correct it for extinction using the Schlafly & Finkbeiner (2011) corrections to the Schlegel et al. (1998) extinction maps, assuming the extinction ratios $A_G/A_V = 0.85926$, $A_{G_{BP}}/A_V = 1.06794$, $A_{G_{RP}}/A_V = 0.65199$, as listed on the web interface to the PARSEC isochrones (Bressan et al. 2012). Henceforth, all magnitudes and colors refer to these extinction-corrected values. For this data selection, we also make cuts in Gaia’s color (0.40 < $[G_{BP} - G_{RP}]$ < 1.60) and the magnitude ($G_0 < 20$) space. The color window ensures the inclusion of the GD-1 like stellar populations, discarding most of the disk contaminants. The chosen magnitude limit mitigates against the effect of completeness variations due to inhomogeneous extinction. We set constraints also in the proper motion ($\sqrt{\mu^2 + \mu^2} > 2$, where $\mu_\alpha \equiv \mu_\alpha \cos \delta$) and the parallax ($\pi < 0.33$ mas at 3$\sigma$ level) selection in order to include only those stars that inhabit a similar phase-space region as GD-1. Henceforth, for convenience, we will drop the asterisk superscript from $\mu^*_\alpha$. This sample of stars was then cross-matched with the spectroscopic surveys of SEGUE (SDSS DR10, Yanny et al. 2009) and LAMOST DR4 (Zhao et al. 2012) data sets in order to acquire their line-of-sight velocities ($v_{\cos}$) that are missing in Gaia DR2. From these cross-matches we obtained their $v_{\cos}$ and [Fe/H] measurements. We then imposed a very conservative metallicity cut in the cross-matched catalog, selecting stars with [Fe/H] < −1.5 (consistent with GD-1’s metallicity, following Malhan & Ibata 2019), to retain a maximal population of GD-1-like stars and reject most of the contaminants. We retain this filtered data set and refer to this as sample-1.

2.2. Anatomy of the GD-1 Stream

In Malhan & Ibata (2019) we performed an orbit-fitting procedure for the GD-1 stars, although to a more conservative star sample (in particular, the spatially extended component was rejected), in order to constrain the gravitational potential of the Milky Way. One of the natural byproducts of the study was the best-fit orbit model for the GD-1 stream. We use the same orbit model here for the purpose of selecting stars in sample-1. First, we analyze the stars contained in a very narrow and restricted phase-space region around GD-1. This was done by sigma-clipping and selecting only those stars in sample-1 that lie within 1.5$\sigma$ of the orbit model in the observed phase-space parameters ($\phi_1$, $\phi_2$, $v_\pi$, $\mu_\alpha$, $\mu_\delta$, $v_{\cos}$). Here, $\phi_1$, $\phi_2$ refer to the angles of the GD-1 coordinate system as mentioned previously, $v_\pi$, $\mu_\alpha$, $\mu_\delta$ are the parallax and proper motion measurements that come from the Gaia data, and $v_{\cos}$ refers to the heliocentric line-of-sight velocity obtained from our cross-matches with the SEGUE and LAMOST catalogs. This stringent selection ensures the rejection of any datum that is even remotely an outlier. Simultaneously, we also clip the data in Gaia’s color–magnitude ($G_0$, $[G_{BP} - G_{RP}]$) space using the same SSP model that previously allowed GD-1’s detection. This very fine selection yields a total of 40 stars (35 from SEGUE and 5 from LAMOST), that represent very-high-confidence GD-1 candidate members. These stars are shown in Figure 2.

We then test if this stringent sample selection of GD-1 members contains only a unimodal stellar component (GD-1...
The orbital model of GD-1 is shown as a dashed curve, yielding 40 stars that are shown here. The free parameters for our model were then provided as a component Gaussian model, one component to account for the stream itself and the other for any possible secondary feature. We investigate this using a generative model, which we take to be a two-component Gaussian model, one component to account for the stream itself, that is 40 stars that are shown here. The likelihood function was expressed as

$$L = \prod_d \left\{ \frac{f_s}{\sqrt{2\pi w_s E(p, w_s)}} \exp \left[ -\frac{1}{2} \left( \frac{\phi^m_d - \phi^d}{w_s} \right)^2 \right] + \frac{f_c}{\sqrt{2\pi w_c E(p, w_c)}} \exp \left[ -\frac{1}{2} \left( \frac{\phi^m_c - \phi^c}{w_c} \right)^2 \right] \right\}\phi_d, \quad (1)$$

where $f_c \equiv 1 - f_s$. Here $\phi_d^m$ is the observed position of a data point, and the corresponding orbit model value is given by $\phi_d^c$. Note that because we are interested in measuring the physical dispersion of the structure(s) in the direction perpendicular to the GD-1’s orbit, this calculation is made only in the position space for the $\phi_d$ coordinate. $E(p, w)$ is the error function that is included as a modification to the normalization of the Gaussian function. This factor takes into account the sigma-clipping procedure that we undertake for the data selection, which abruptly truncates the data at a given $\sigma$-value. Here, it is defined as $E(p, w) = \text{erf}(p/w\sqrt{2})$, and in this case $p = 1.5$. We then sample the posterior probability distribution function (PDF) with an MCMC algorithm. The resulting PDF is shown in Figure 3. The PDFs are well behaved and suggest that the data set under inspection contains only a single unimodal structural component, since $f_s \to 1$ ($f_c \to 0$), this suggests that the 1.5$\sigma$ selection does not show significant evidence of any secondary features, and consists of only a unimodal structural component, GD-1 itself, that is 40 $\pm$ 10 pc wide. This is not surprising, as the stringent sample selection (made in the multi-dimensional volume of phase-space and photometry information) can barely accommodate any additional structural feature.
component was identified with a physical width of \( \langle w_c \rangle = 110 \pm 20 \text{ pc} \), with 37\% \( (f_c = 0.37) \) of the stars belonging to this newly identified component \((\approx 43 \text{ stars})\). We dub this component the cocoon of GD-1. The revised physical width of the narrow component is found to be \( \langle w_c \rangle \approx 30 \text{ pc} \).

We also realized that such a relaxed selection, although made in the multi-dimensional volume of phase-space and photometry information, may also gather stars from the structures lying in GD-1’s neighborhood (shown in Figure 1(d)). Therefore, in order to ascertain that this newly identified cocoon component is not a reflection of these surrounding localized structures, we repeat our previous analysis, except this time masking the sky regions where GD-1’s neighboring structures lie. To mask the spur, for instance, we first approximate its on-sky trajectory from the map of Bonaca et al. (2019) and adopt its width to be 0°2, per their study. We repeat the same for the PS1-E stream (Bernard et al. 2016), and set its width at 0°3. These models (or masked regions) are shown in Figure 4 (top panel), and the stars lying in these regions were then removed. We do not mask the Gaia-5 stream region because although it happens to be located close to GD-1 in the sky, Gaia-5’s proper motions are significantly different from those of GD-1 (Malhan et al. 2018b), hence it is not enclosed in the 5\( \sigma \) threshold selection that we make here. This masked selection, in contrast to the previous unmasked case, yields a total of 109 stars (98 from SEGUE and 11 from LAMOST). We again find a bimodal distribution of stars, but with a slight variation in our parameter values. This time, the secondary component was identified with a physical width of \( \langle w_c \rangle = 130^{+30}_{-20} \text{ pc} \), with 22\% \( (f_c = 0.22) \) of the stars belonging to this extended component \((\approx 24 \text{ stars})\). The observed dip in the cocoon’s signal strength in this case is expected, as the seven stars that were now masked previously lay in the exterior region of GD-1, thereby contributing to the cocoon signal.

Having established the presence of a secondary extended stellar component, we then take the likelihood ratio test to assess the need for the presence of two populations rather than just one. For this, we used the unmasked (masked) data sample of 116 (109) stars as above, and fitted them using the same double-Gaussian model, except this time forcing \( f_c = 0 \) and \( w_c = 1 \) (the value of \( w_c \) is unimportant given that \( f_c \) is set to zero). The corresponding \( p \)-value with respect to the fully free model above is \( p = 1.46 \times 10^{-6} (\rho = 1.18 \times 10^{-7}) \), indicating that the simpler model with a single unimodal width distribution can be rejected with high confidence at the 5\( \sigma \) (5\( \sigma \)) level. Hence, the evidence for an additional component appears to be strong. Note that the estimated value of \( w_c \) in our analysis is sensitive to the phase-space volume probed for the data selection (set to a 5\( \sigma \) threshold width here), nevertheless it can be perceived to be a lower bound. This means that in reality the detected cocoon structure may be spatially extended to even greater distances from GD-1, as was initially suggested by Figure 1(b). This property is also revealed by the synthetic...
streams that are produced in cosmological simulations (we discuss this in Section 4 below).

3. Cocoon or Contamination?

In order to ascertain the existence of this cocoon feature, it is important to ensure that it is not an artifact of the underlying background contamination that lies in the region of the sky containing GD-1. To examine this issue, and to quantify the contamination level present along GD-1’s orbital track, we followed a tailor-made test that we now describe.

We take GD-1’s orbit model and shift it by $+10^\circ$ in $\phi_2$, keeping its configuration fixed in the other phase-space dimensions, and count the number of stars that get selected by the orbit within $5\sigma$ from sample-1 in the same fashion as discussed before. This is shown in Figure 6(a). In this case, the selection around the orbit draws zero contaminants. We repeat this procedure for $+5^\circ$, $-5^\circ$, $-10^\circ$ shifts in $\phi_2$ from the $0^\circ$ reference point, and respectively, find that only 2, 3, and 4 contaminants are selected around the orbit. Thus, the observed level of cocoon members is unlikely to be due to random contaminants.

Next, in order to extract out the information on the spatial extent of the cocoon we do the following. Keeping GD-1’s orbit model fixed at its original position, we make a $3\sigma$ threshold selection of the data points in proper motion, parallax, photometry, and line-of-sight velocity information space. For each selected datum, the angular difference $\Delta \phi_2$, between the GD-1’s orbital model and the observed value, is calculated and the data is binned at that value. The corresponding stellar density distribution is shown in Figure 6(b). The narrow peak at $\phi_2 \sim -0.1^\circ$ shows the presence of the “thin” component of the GD-1 stream, while the broadened distribution reveals the presence of the cocoon that extends out to $\sim 1^\circ$ in either direction.

4. Interpreting the “Cocoon” with Cosmological Simulations

In order to interpret our findings, we turn to a set of cosmological simulations. In this section, we first describe the simulation setup, followed by the interpretation of the identified cocoon phenomenon.

The simulation used here to illustrate the formation of stream cocoons is essentially the same as that developed in Carlberg (2018a). The simulation started with the Via Lactea II halo catalog at redshift 3. The halos were reconstituted as Hernquist spheres (Hernquist 1990) using dark matter particles of mass
Figure 6. Left panel: checking for contamination along GD-1’s track. The gray background shows the field star number density of our sample-1 data as obtained in Section 2 via cross-matching the Gaia DR2 catalog with the SEGUE and LAMOST data sets. This density map appears patchy due to the non-uniform sky coverage of these two spectroscopic surveys. GD-1’s orbital track is shown in cyan. We shifted this track in the \( \phi_2 \) coordinate, using different values of \( \phi_2 \) as marked in the diagram, to test the level of field star contamination in the surrounding regions. A 5\( \sigma \) threshold for selection was used throughout. The number of contaminants found are reported in brackets, and also shown as color points, and are substantially smaller than the number found for the cocoon structure that we detect in this study. Right panel: stellar density distribution, obtained by making a 3\( \sigma \) threshold selection in proper motions, parallaxes, photometry, and line-of-sight velocity with respect to the original GD-1 orbital model. \( \Delta \phi_2 \) refers to the angular difference between the datum and the GD-1 orbit. The green profile reveals a narrow peak at \( \Delta \phi_2 \approx -0.1^\circ \) (the “thin” GD-1 stream), along with a broadened distribution (the cocoon) that extends out to \( \sim 1^\circ \) on either direction. The red and blue regions represent the estimated (on-sky) widths of the thin GD-1 stream and the extended component, respectively.

2 \times 10^4 M_\odot. The 30 heaviest halos (\( \geq 4 \times 10^8 M_\odot \)) were provided with the tidally limited King model star clusters (King 1966) of mass 10^5 M_\odot that were inserted in randomly oriented planes into these halos. The star particles had a mass of 5 M_\odot. The dark matter particles had a softening of 200 pc and the star particles had a softening of 2 pc. The mixture of dark matter and star particles evolved with a modified version of Gadget-2 code (Springel 2005) that provided the expected level of two-body relaxation in the star clusters. There typically are about 300,000 time steps for a simulation run from near redshift 3, an initial age of 2.07 Gyr, to a current epoch age of 13.4 Gyr.

All the simulated star particles were then transformed from the Galactocentric Cartesian frame to the heliocentric (observable) frame using the Sun’s parameters as \( R_\odot = 8.122 \) kpc (Gravity Collaboration et al. 2018) and \( V_\odot = (11.1, 255.2, 7.25) \) km s\(^{-1}\) (Reid et al. 2014; Schönrich et al. 2010). We then selected out only those stars that lay in the region of the sky where \( |\theta| > 20^\circ \) and 5 kpc < \( d_\odot < 20 \) kpc. This choice of location was made to focus on those streams that lie in a similar region of the sky as GD-1, thereby allowing a meaningful comparison. A few of the selected structures (\( \approx 250 \)) structures were reviewed) are shown in Figure 7. In the corresponding figure, each panel (shown in the coordinate system that roughly aligns along the streams) shows only those star particles that came from the same GC progenitor. One can see that all of these streams contain a secondary diffuse stellar component (the cocoon), similar to one that we detect here for the GD-1 stream. But how does this secondary feature actually form? The origin of this phenomenon becomes clear by examining the evolution of GCs in the simulation.

Process of cocoon formation: in the simulation, all the stars start in GCs. These GCs are placed into a disk-like distribution in the dark matter sub-halos (Mayer et al. 2001) on nearly circular orbits with radii of \( \sim 1 \) kpc. As the tidal fields of these sub-halos begin to strip off the stars from the GCs a “donut” of stars is formed that is initially dispersed around the \( \sim 1 \) kpc orbit (see Figure 8). Once the sub-halo falls into the main halo, its dark matter merges with the main halo (partially or completely) and the GC, along with the dispersed stars, gets deposited into the main halo. The GC now releases stars on its new orbit in the main halo, forming the thin and dense part of the stream, while the stars that were spread out in the “donut” like shape end up creating a broader stream enveloping the thin stream structure. Both the thin stream and the cocoon finally end up on quite similar orbits. These different phases of GC’s dynamical evolution are illustrated in Figure 8.

This picture can now provide an explanation of the newly identified cocoon component we have found in this paper. According to this framework, GD-1’s progenitor GC originally formed inside a “dwarf galaxy” dark matter sub-halo, and was brought into the Milky Way during the accretion of the parent sub-halo. Our qualitative study of synthetic streams further suggests that the accompanying cocoon structure is most likely a ubiquitous characteristic that is exhibited by all the streams that are remnants of the accreted GCs that came along within their satellite galaxies.

We also carried out a quantitative analysis with one of the synthetic streams to test if they too reveal a bimodal distribution, similar to that shown above for GD-1. To this end, we first selected a candidate structure from our set of synthetic streams that shared similar structural and orbital properties to those of GD-1. We chose the stream shown in Figure 7(b), as it possessed a physical length, spanning distance, and \( L_c \) value similar to those of GD-1. The stream is also shown in Figure 9. Once again, we fit the same double-Gaussian model via an MCMC process. To make a meaningful comparison with the GD-1 case, here we analyzed only those star particles that roughly lie within the physical width that was effectively equivalent to the 5\( \sigma \) selection width of the GD-1 stars. Also, note that in this case we lack a corresponding orbital model for the stream (that basically goes into the Equation (1) in the form of the parameter \( \phi_2 \)). For this, we allow \( \phi_2 \) \((m \) in the present case) to be an additional parameter of our model that is fitted to the data using the polynomial
parameterization of the form
\[ \eta^m = a + b\zeta + c\zeta^2, \]
where \(a, b, c\) are the intrinsic parameters of \(\eta^m\) that are actually sampled during the MCMC exploration. The physical dispersions of the two structural components (the stream and the cocoon) are then calculated about the fitted \(\eta^m\). The results obtained in this case are shown in Figure 9. As expected, we find a bimodal distribution of the particles corresponding to a thin structure and an accompanying diffuse component. In this case, the secondary component was identified with a physical width of \(\langle \omega_c \rangle = 130 \pm 10\) pc (comparable to the size of GD-1’s cocoon); however, note that the structure actually extends well beyond this range, similar to the range displayed in Figure 1(b)). The similarity between the results obtained in this case, by analyzing synthetic stream structures from the cosmological simulations, with the ones obtained for the GD-1 case, that was based on astrophysical data, establishes both the plausibility of the existence and the positive detection of the cocoon structure around the GD-1 stream.

5. Conclusion and Discussion

We investigated the structure and morphology of the GD-1 stellar stream in order to understand its embryonic origin and its participation in the formation of the Milky Way halo. Being a remnant of a GC, GD-1 is often conceived of as a simple system that is usually approximated as a linear structure. Our study here suggests otherwise.

Using the 6D phase space and photometric measurements, we probed the sky region around the GD-1 stream and found evidence for the presence of an additional extended and diffuse stellar component (which can be seen in Figure 1(b)). This secondary component, which we dub the cocoon here, was detected at a \(\geq 5\sigma\) confidence level. The physical width of the cocoon was found to be \(\langle \omega_c \rangle = 110 \pm 20\) pc (Figures 4, 5), which we obtained by analyzing the 6D phase space and color-magnitude region within the \(5\sigma\) volume around the GD-1 stream. Additionally, the revised physical width of the narrow component was estimated to be \(\langle \omega_c \rangle \sim 30\) pc. To interpret this detection, we turned to a set of cosmological simulations, and found that this cocoon feature is most likely a ubiquitous characteristic that is exhibited by all the streams that are remnants of the accreted GCs that came within dwarf galaxy-mass dark matter sub-halos.

The highly retrograde nature of GD-1’s orbit (\(L_z \sim 3000\) km s\(^{-1}\) kpc, see Figure 10, Malhan & Ibata 2019), together with its metal-poor stellar population, paints a picture that appears consistent with this scenario. This is because more retrograde motions and lower metallicities in the outer galactic halo are indicative of accretion of low-mass galaxies (Carollo et al. 2007). Moreover, the detection of the cocoon means that GD-1’s progenitor was still within the “dwarf galaxy” dark halo prior to the merging of the dark matter sub-halo onto the main halo.

In principle, there are other physical processes that can also give rise to similar extended and diffuse components in (otherwise) thin stellar streams. The thick component could be produced by the perturbation effects of the stream’s interaction with other massive galactic components, such as by shocks from the disk. However, GD-1’s disk crossings take place between 13 and 23 kpc from the Galactic center, where the disk density is too low to significantly impact the stream (Bonaca et al. 2019). Interactions with dark matter sub-halos could also result in the heating of stellar streams (Ibata et al. 2002; Johnston et al. 2002; Siegal-Gaskins & Valluri 2008; Carlberg et al. 2012; Erkal et al. 2016). However, GD-1’s velocity dispersion is as low as \(\sim 1.5\) km s\(^{-1}\) (Malhan & Ibata 2019), indicating dynamical coldness of this system, that suggests that so far GD-1 has not suffered substantial external heating. Recently, Carlberg (2018b) argued that another contribution to stream density variations could also stem from the GC streams having traversed the large-scale tidal field of the host galaxy, which varied over time as the galaxy assembled.
The cosmological simulations suggest that we have possibly found an unambiguous means of distinguishing between the in situ and ex situ formed GC streams population, which otherwise can be hard to disentangle. The number of streams identified in this manner should in principle place a lower limit on the number of past accretion events, allowing one to quantify the number of stars in the stellar halo that are a result of hierarchical merging events (Bullock & Johnston 2005).

Although here we studied only a single GC stream, making the...
case for the discovery of the cocoon phenomenon, it would be interesting to analyze other GC streams of the Milky Way in order to examine if the cocoon property is ubiquitous, or is limited only to particular types of GC streams.

The simulations that we studied here show a large diversity in the structural morphology of the cocoon component (Figure 7); nevertheless, the phenomenon was found to be ubiquitous among all the accreted GC streams. The morphology would of course depend on the orbital history of the accreted satellite, but it may retain information about its now defunct dark nursery. Through careful N-body modeling of the GD-1 stream, which can simultaneously reproduce its cocoon, it may be possible to constrain the initial conditions of the parent dark matter sub-halo. For instance, the cocoon’s phase-space density may be linked with the dark matter density profile and its phase-space dispersion with the mass and the physical size of the dark sub-halo. For example, it is known that for the same set of initial conditions the GC stripping occurring in a “cuspy” dark matter profile is relatively more pronounced than that in a “cored” profile (because force fields in constant density profiles are rather compressive in nature; Cole et al. 2012; Petts et al. 2016; Contenta et al. 2018). In such a case, “cuspy” profiles are expected to form a denser cocoon, which can then ultimately get reflected in the morphology of the accreted stream and cocoon system. This would of course also be sensitive to the initial phase-space position of the GC within the dark sub-halo. Such a study, employing the cocoon as a dark matter probe, may open a window into the premerging times by revealing the physical properties of the primordial dark sub-halos. The inferred properties, in principle, could be different from those that are currently observed for the dwarf galaxies. Such a comparison would also be useful in understanding and testing the galaxy evolution paradigms and cosmological models for the lowest-mass halos.

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References

Bellazzini, M., Ferraro, F. R., & Ibata, R. 2003, AJ, 125, 188
Bernard, E. J., Ferguson, A. M. N., Schlaufly, E. F., et al. 2016, MNRAS, 463, 1759
Bianchini, P., Sills, A., & Miholics, M. 2017, MNRAS, 471, 1181
Bonaca, A., Hogg, D. W., Price-Whelan, A. M., & Conroy, C. 2019, ApJ, 881, 38
Bressan, A., Marigo, P., Girardi, L., et al. 2012, MNRAS, 427, 127
Bullock, J. S., & Johnston, K. V. 2005, ApJ, 635, 931
Carlberg, R. G. 2018a, ApJ, 861, 69
Carlberg, R. G. 2018b, arXiv:1811.10084
Carlberg, R. G., Grillmair, C. J., & Hetherington, N. 2012, ApJ, 760, 75
Carollo, D., Beers, T. C., Lee, Y. S., et al. 2007, Natur, 450, 1020
Cole, D. R., Dehnen, W., Read, J. I., & Wilkinson, M. I. 2012, MNRAS, 426, 601
Contenta, F., Balbinot, E., Petts, J. A., et al. 2018, MNRAS, 476, 3124
de Boer, T. J. L., Belokurov, V., Koposov, S. E., et al. 2018, MNRAS, 477, 1893
Erkal, D., Belokurov, V., Bovy, J., & Sanders, J. L. 2016, MNRAS, 463, 102
Forbes, D. A., Bastian, N., Gieles, M., et al. 2018, RSPSA, 474, 20170616
Freeman, K., & Bland-Hawthorn, J. 2002, ARA&A, 40, 487
Gaia Collaboration, Helmi, A., van Leeuwen, F., et al. 2018, A&A, 616, A12
Gravity Collaboration, Abuter, R., Amorim, A., et al. 2018, A&A, 615, L15
Grillmair, C. J., & Dionatos, O. 2006, ApJL, 643, L17
Helmi, A. 2008, A&ARv., 15, 145
Henriques, L. 1990, ApJ, 356, 359
Ibata, R. A., Lewis, G. F., Irwin, M. J., & Quinn, T. 2002, MNRAS, 332, 915
Ibata, R. A., Malhan, K., & Martin, N. F. 2019, ApJ, 872, 152
Ibata, R. A., Malhan, K. N., & Martin, N. F. 2019, ApJ, 872, 152
Johnston, K. V., Spergel, D. N., & Haydn, C. 2002, ApJ, 570, 656
King, I. R. 1966, AJ, 71, 64
Koposov, S. E., Rix, H.-W., & Hogg, D. W. 2010, ApJ, 712, 260
Lindgren, L., Hernandez, J., Bombrun, A., et al. 2018, A&A, 616, A2
Malhan, K., & Ibata, R. A. 2018, MNRAS, 477, 4063
Malhan, K., & Ibata, R. A. 2019, MNRAS, 486, 2993
Malhan, K., Ibata, R. A., Goldman, B., et al. 2018a, MNRAS, 478, 3862
Malhan, K., Ibata, R. A., & Martin, N. F. 2018b, MNRAS, 481, 3442
Mayer, L., Governato, F., Colpi, M., et al. 2001, Ap&SS, 276, 375
Miholics, M., Webb, J. J., & Sills, A. 2016, MNRAS, 465, 240
Petts, J. A., Read, J. I., & Gualandris, A. 2016, MNRAS, 463, 858
Price-Whelan, A. M., & Bonaca, A. 2018, ApJL, 863, L20
Reid, M. J., Menten, K. M., Brunthaler, A., et al. 2014, ApJ, 783, 130
Schlafly, E., & Finkbeiner, D. P. 2011, BAAS, 43, 434.22
Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, ApJ, 500, 525
Schönrich, R., Binney, J., & Dehnen, W. 2010, MNRAS, 403, 1829
Searle, L., & Zinn, R. 1978, ApJ, 225, 357
Siegal-Gaskins, J. M., & Valluri, M. 2008, ApJ, 681, 40
Springel, V. 2005, MNRAS, 364, 1105

Wagner-Kaiser, R., Mackey, D., Sarajedini, A., et al. 2017, MNRAS, 471, 3347
Webb, J. J., & Bovy, J. 2019, MNRAS, 485, 5929
Yanny, B., Rockosi, C., Newberg, H. J., et al. 2009, AJ, 137, 4377
Zhao, G., Zhao, Y., Chu, Y., Jing, Y., & Deng, L. 2012, arXiv:1206.3569