Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY
MNRAS **525,** L72–L75 (2023) https://doi.org/10.1093/mnrasl/slad098
Advance Access publication 2023 July 18

The dual nature of the tidal tails of NGC 5904 (M5)

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Accepted 2023 July 14. Received 2023 July 5; in original form 2023 May 27

ABSTRACT

The tangential velocity dispersion of stars belonging to the Milky Way globular cluster's tidal tails has recently been found from *N*-body simulations to be a parameter that distinguishes between cored and cuspy profiles of low-mass dwarf galaxy dark matter subhaloes where that globular cluster formed, and the *in situ* formation scenario. In this context, we discovered that M5's tidal tails are composed by stars at two different metallicity regimes ([Fe/H] ~ -1.4 and -2.0 dex). The more metal-rich tidal tail stars are of the same metal content than M5's members and have a tangential velocity dispersion that coincides with the predicted value for a cuspy formation scenario (subhalo mass $\sim 10^9$ M$_\odot$). The more metal-poor stars, that are found along the entire M5 tidal tails and have similar distributions to their more metal-rich counterparts in the M5 colour–magnitude diagram and orbit trajectory, have a tangential velocity dispersion that refers to a cored subhalo (mass $\sim 10^9$ M$_\odot$), or an *in situ* formation scenario. In order to reconcile the dual distribution of M5 tidal tail stars, in kinematics and chemistry, we propose that M5 collided with another more metal-poor and less-massive globular cluster anytime before or after it was accreted into the Milky Way.

Key words: methods: numerical – globular clusters: general – globular cluster: individual: M5.

1 INTRODUCTION

Some recent detection of tidal tails of Milky Way globular clusters using clustering search techniques in an *N*-dimensional phase space assume that their stars and those belonging to the cluster have similar proper motions. In general, an upper limit of 2 mas yr^{-1} around the mean cluster proper motion has been used to identify tidal tails stars, which have been called a cold stellar stream (Sollima 2020; Yang et al. 2022; Koposov et al. 2023). However, because of tidal tails stars have speed up their pace in order to escape the cluster, their proper motions can be different from the cluster mean proper motion. There are, additionally, other reasons that can contribute to make the space motion of tidal tails stars different from the mean cluster space velocity, among them, projection effects of the tidal tails, the Milky Way tidal interaction, the intrinsic kinematic agitation of a stellar stream (Wan et al. 2023).

Furthermore, some stellar streams have resulted to be kinematically hot, like the C-19 stream (Yuan et al. 2022), which has been found to be dominated by a dark matter halo (Errani et al. 2022). Rising velocity dispersion profiles toward the outer regions of globular clusters were also suggested by Carlberg & Grillmair (2021) for globular clusters placed at the centre of dark matter mini haloes; a behaviour that was also explained by the effects of the Milky Way tidal interaction (Vitral & Boldrini 2022). Recently, Malhan et al. (2022) showed that globular clusters formed in low-mass dwarf galaxy dark matter subhaloes, later accreted into the Milky Way, have tidal tails with a mean tangential velocity dispersion larger than that for tidal tails of globular clusters formed *in situ*. Based on these outcomes, globular cluster origins could be inferred by differentiating whether their tidal tails are kinematically cold (*in situ* formation) or hot (accreted origin).

Although some globular clusters do not present tidal tails (Zhang, Mackey & Da Costa 2022), it is worth measuring the tangential velocity dispersion of globular cluster tidal tails in order to distinguish those formed in cored or cuspy cold dark matter subhaloes (those accreted) from those formed in the Milky Way. These outcomes can be useful, for instance, to know the nature of the dwarf galaxy dark matter subhaloes where the clusters formed, the mass of those subhaloes, as well as to confirm the previous known associated origins of the Milky Way globular clusters (e.g. Massari, Koppelman & Helmi 2019). We embarked in this challenging analysis by examining the tidal tails of NGC 5904 (M5), a globular cluster associated to one of the latest merger events occurred in the Milky Way (Kruijssen et al. 2019; Forbes 2020).

In this Letter, we report the discovery of the dual nature of the tidal tails of M5. They contain stars both in the cored and cuspy formation scenarios, which in turn have clearly different overall metallicity contents. In Section 2, we present the analysis of the data, while in Section 3, we speculate on a possible scenario for the resulting outcomes.

2 DATA ANALYSIS

Grillmair (2019) detected using the second release of the *Gaia* database (Gaia Collaboration 2016; Babusiaux et al. 2023) a long trailing tidal tail extending westward from M5. He selected 50 highest ranked tidal tail member candidates based on their similar distances, their magnitudes and colours distributed along the M5 colour–magnitude diagram, their proper motions consistent with the cluster's trajectory at a detection significance $\approx 10\sigma$. The long tidal

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tail is included in the recent atlas of Milky Way streams compiled by Mateu (2023). We used the derived *Gaia* DR3 parameters[1] for these 50 stars to compute their tangential velocities.

The top-left panel of Fig. 1 shows the distribution of the stars in the sky. As for their physical distances, we relied on the results found by Grillmair (2019) and Ibata et al. (2021), who place the long tidal tail at a constant distance, that of the M5's mean heliocentric distance (7.48 kpc; Baumgardt & Vasiliev 2021), as is illustrated by the solid line in the parallax versus RA plot drawn in the top-right panel of Fig. 1. Hence, we adopted for the subsequent analysis the RA coordinates as the tidal tail tracing coordinates.

The tangential velocities were computed as $V_{\rm Tan} = k \times d_\odot \times \mu$; where $k = 4.7405$ km s^{-1} kpc^{-1} (mas/yr)$^{-1}$, $d_\odot$ is the tidal tail distance, and $\mu = \sqrt{\mu_\alpha^{*2} + \mu_\delta^2}$, with μ_α^* and μ_δ being the proper motions in RA and Dec as provided by *Gaia* DR3. We used fig. 15 of Ibata et al. (2021) to estimate the mean $d_\odot$ for intervals of Δ(RA) $= 5^\circ$, and used those values to compute $V_{\rm Tan}$ for stars in the respective RA bins. The bottom-right panel of Fig. 1 shows the observed relation between $V_{\rm Tan}$ and RA. The error bars come from propagation of errors of the $V_{\rm Tan}$ expression. We then fitted a second order polynomial function, represented by the solid line in the bottom-right panel of Fig. 1, and computed the difference between the measured $V_{\rm Tan}$ values and the corresponding ones on the fitted function for the respective RA.

In order to obtain the tangential velocity dispersion, we derived the dispersion of the resulting residual distribution by employing a maximum likelihood approach (see, e.g. Pryor & Meylan 1993; Walker et al. 2006). For that purpose, we optimized the probability $\mathcal{L}$ given by:

$$\mathcal{L} = \prod_{i=1}^{N} \left(2\pi\,(\sigma_i^2 + W^2)\right)^{-\frac{1}{2}} \exp\left(-\frac{(\Delta(V_{\rm Tan})_i - <\Delta(V_{\rm Tan})>)^2}{2(\sigma_i^2+W^2)}\right),$$

where $\Delta(V_{\rm Tan})_i$ and σ_i are the residual $V_{\rm Tan}$ value and the corresponding error for the i-th star. We obtained a mean tangential velocity dispersion $W = 15.65 \pm 0.47$ km s^{-1}. This result largely exceeds the highest predicted tangential velocity dispersion for globular cluster streams in dark matter subhaloes with a mass of 10^9 M$_\odot$ (~ 8.5 km s^{-1}).

We used the overall metallicity estimates ([Fe/H]) and their uncertainties provided by GSP-Phot in *Gaia* DR3 to check whether the resulting W value can be biased by the presence of field stars. Only 25 out of the 50 stars have available *Gaia* DR3 metallicities. For them, we first corrected the [Fe/H] values following the prescriptions given by Andrae et al. (2023)[2] and then plotted the resulting values as a function of RA (see bottom-left panel of Fig. 1). As can be seen, there are two different metallicity regimes, centred at [Fe/H] ~ -1.4 and -2.0 dex, respectively. For each of them, we repeated the above procedure to compute the tangential velocity dispersion, and obtained $W = 7.50 \pm 1.38$ km s^{-1} and 2.00 ± 4.07 km s^{-1}, for the more metal-rich and more metal-poor samples, respectively. For the most metal-rich regime, we did not consider the star at [Fe/H] ≈ -0.5 dex, because it is beyond the mean value by more than seven times the metallicity dispersion. We finally searched the *Gaia* DR3 database looking for M5 members with metallicity estimates, with the aim of validating the above procedure and results. We applied the selection cuts as in Vasiliev & Baumgardt (2021), selecting stars with μ_α^* and μ_δ values within the dispersion found by Baumgardt et al. (2019),[3] `ruwe` < 1.15, `visibility_periods_used` ≤ 10, and `ipd_frac_multi_peak` ≤ 2. We found four stars within the cluster area (<5′) with corrected [Fe/H] values of ~ -1.4 dex, which is in excellent agreement with the known M5 metal content ([Fe/H] $= -1.33$; VandenBerg, Casagrande & Edvardsson 2022, and references therein).

[1] Kindly provided by Cecilia Mateu.

[2] https://www.cosmos.esa.int/web/gaia/dr3-gspphot-metallicity-calibration

[3] https://people.smp.uq.edu.au/HolgerBaumgardt/globular/

3 DISCUSSION AND CONCLUSIONS

M5, with an age of 11.46 ± 0.44 Gyr (VandenBerg et al. 2022), is associated to the Helmi stream, the aftermath of a merger event (5–8 Gyr) of a small mass dwarf galaxy experienced by the Milky Way (Kruijssen et al. 2019;Massari et al. 2019; Forbes 2020). Its orbit eccentricity (0.79 ± 0.01) and inclination (74.09 ± 0.66°) also witness its accreted origin (Piatti, Webb & Carlberg 2019). If we entered in the bottom panel of Fig. 1 of Malhan et al. (2022) with W = 7.5 km s^{-1} – the present tangential velocity dispersion for M5 tidal tail stars with similar cluster metallicities – we would find that the cluster formed in a dwarf galaxy dark matter subhalo with a cuspy profile with a mass of $\sim 10^{8.8\pm0.1}$ M$_\odot$. Therefore, we can conclude that this component of the stream is consistent with that formation scenario.

However, the dual metallicity distribution found among the highest ranked tidal tail candidate members hampers our smooth understanding of the M5's origin. Stars at both metallicity regimes are found distributed along the entire extension of the examined tidal tail (see Fig. 1), which undoubtedly removes any speculation that most of them are unrelated stars to M5. On the other hand, overall metallicity differences Δ[Fe/H] larger than ~0.6 dex (see Fig. 1) were found in the building block globular clusters Terzan 5 Romano (2023) and Liller 1 (Crociati et al. 2023) in the Milky Way and M54 (Alfaro-Cuello et al. 2019) in the Sagittarius dwarf spheroidal galaxy. We note that the difference in metallicity between M5 1G and 2G stars is 0.03 dex (Marino et al. 2019). Hence, M5 would not seem to belong to that globular cluster group, since it does not show the expected age spread (see its *Hubble Space Telescope* colour–magnitude diagram in VandenBerg et al. 2022) for a long star formation history as observed in those building block globular clusters. Therefore, we can conclude that only tidal tail stars with a metallicity similar to that of M5 were born in the cluster itself. Because of the remarkable different metallicity, and according to the known nucleosynthesis processes, the more metal-poor tidal tail stars could not form in M5.

The mean tangential velocity dispersion of the more metal-poor stars ($W = 2.00$) matches the cored dark matter subhalo formation scenario (mass $\sim 10^9$ M$_\odot$) in the N-body simulation performed by Malhan et al. (2022). If this were the case, then these more metal-poor stars could be the relics of a globular cluster formed in another dwarf galaxy, that collided with M5. Note that the lack of metallicity spread among them (see Fig. 1) discards any possible accretion of stellar structures with a long star formation history or scattered field stars. The collision could take place before M5 was accreted into the Milky Way or in the Milky Way itself, after they were accreted into the Galaxy, separately. Because of the uncertainty in the resulting W value ($\sigma W = 4.07$ km s^{-1}) the more metal-poor stars could also be the fossils of a globular cluster formed *in situ* that collided with M5. Whatever the scenarios is considered, it would seem that a reasonable interpretation for the dual nature of stars belonging to the tidal tails of M5, in kinematics and chemistry, is that the cluster experienced an encounter with another globular cluster.

This speculation opens this research field to further analyses. Indeed, a spectroscopic survey of tidal tails stars in M5 is mandatory, as well as in M5's main body. According to the number of analysed tidal tail stars with metallicity estimates, the putative colliding cluster

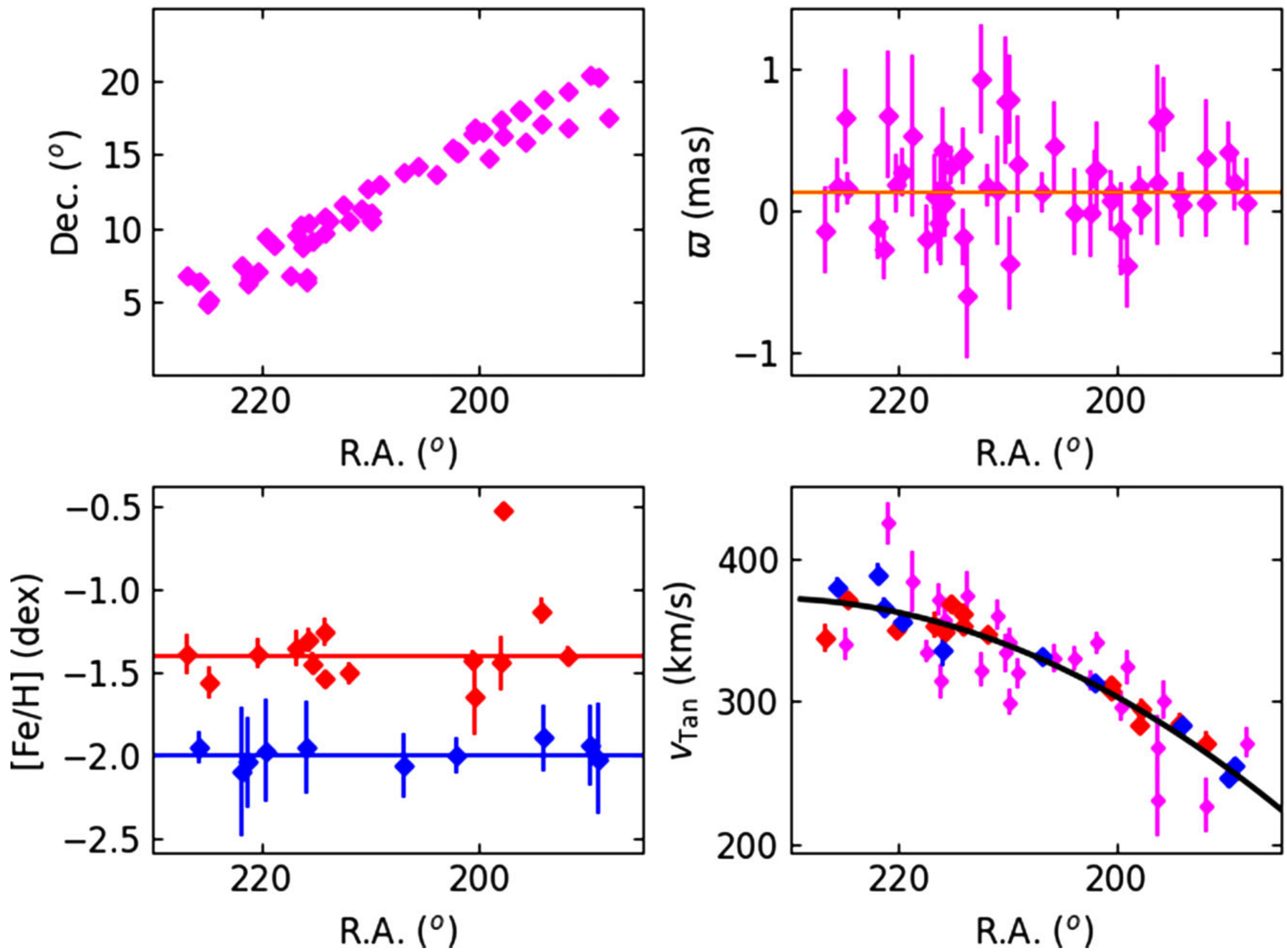

Figure 1. Highest ranked candidate tidal tail stars according to Grillmair (2019). Data were taken from Mateu (2023). The orange line in the upper-right panel represents the mean cluster parallax derived by Baumgardt & Vasiliev (2021). Mean *Gaia* metallicities and uncertainties are corrected according to Andrae et al. (2023); the red and blue lines represent the mean values of red and blue points, respectively. A quadratically least-square fit is shown in the v_{Tan} versus RA plane for all the data, included those without metallicities (magenta points).

could contain ∼1/3 of the M5's tidal tail mass. We also wonder whether some stars of such a disrupting cluster could be trapped within the M5's main body. Alternatively, future *N*-body simulations will be very useful to analyse this scenario in detail. El-Falou & Webb (2022) simulated a dwarf galaxy passing within the M5's tidal tails and found that it is negligibly perturbed by the dwarf galaxy. In case future simulations find that the collisional scenario is feasible, then that would further imply that observations of metallicity spread in M5 do not necessarily require multiple episodes of star formation, but that it can occur as a result of collision between two globular clusters hosting different stellar populations. The speculated collision between M5 and another more metal-poor globular cluster is not the prototypical phenomenon proposed by theories of the formation of globular clusters, however its discovery is both encouraging and interesting. Therefore, M5 provides a unique laboratory to explore various new aspects of formation and evolution theory of globular clusters.

ACKNOWLEDGEMENTS

We thank the referee for the thorough reading of the manuscript and timely suggestions to improve it. This work has made use of data from the European Space Agency (ESA) mission *Gaia* (https://www.cosmos.esa.int/gaia), processed by the *Gaia* Data Processing and Analysis Consortium (DPAC, https://www.cosmos.esa.int/web/gaia/dpac/consortium). Funding for the DPAC has been provided by national institutions, in particular the institutions participating in the *Gaia* Multilateral Agreement.

DATA AVAILABILITY

Data used in this work are available upon request to the author.

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