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ABSTRACT

Numerous stellar streams that have been discovered in the Milky Way as evaporated globular clusters (GCs) show signs of dynamical perturbation. N-body models that can illuminate the origin of these perturbations require the cluster’s initial mass as a fundamental input parameter. Here we present orbits and masses of 20 dissolved GCs in the Milky Way. We constrained the streams’ orbits by fitting the 3D positions of a stream’s endpoints from ground-based photometry and its proper motions from Gaia. Assuming a dissolution time of 10 Gyr, we use orbital apocenters and eccentricities to estimate the clusters’ initial mass. Disrupted GCs have preferentially lower masses than the surviving population, with the median mass being an order of magnitude smaller. The overall distribution of apocenters and eccentricities is similar for the disrupted and surviving clusters, however, at a fixed mass disrupted clusters have smaller apocenters and larger eccentricities. The progenitors of tidal streams observed at the present are a specific, low-mass subset of the initial GC population. This has implications for establishing the role of internal dynamics in sculpting the observed tidal debris, and the amount of external perturbation, e.g., from dark-matter subhalos, that these streams experienced.

1. INTRODUCTION

2. STREAM ORBITS

Tidal debris from evaporating GCs nearly delineates the progenitor’s orbit. Here we measure orbital parameters of GCs dissolved in the Milky Way by fitting orbits to sky positions and distances of 51 thin stellar streams.

- for all streams we have sky positions (stream track) and an average distance - sky positions are known extremely precisely, and for orbit fitting we assume uncertain to the width, typically $\lesssim 0.5^\circ$ - distances are more uncertain because mainly from matched filter, typically $\approx 20\%$ - sample the stream at 0.5° , these shown as crosses in figure, colored by distance

- assumed gravitational potential - orbit represented as a 6D point, initialized xdeg from the end of the stream, at the average distance, with the velocity vector pointing to the opposite end of the stream - final free parameter: orbital length - priors: flat (physical – distance positive, velocity lower than 600km/s?), stream length to match data to xdeg - preliminary solution w minimize - start ball there, sample w emcee, 64 walkers advanced for x steps, discard first y steps as burn-in - convergence test: just no motion in median, dispersion?

- results in figure: lines samples from the posterior, also colored by distance - zoom in: track fit very well, orbit fits expect some distance gradients, can be improved in the future w better selected members - orbit xGyr in the future, on average y orbital periods, that we use to measure apocenter R_{apo} , eccentricity, $e = (R_{apo} - R_{peri})/(R_{apo} + R_{peri})$ - within one orbit peri/apo precisely measured (fractional precision x), across samples, median/90 percentile fractional uncertainty for apocenter, eccentricity - two examples: different kinds of orbits, same precision?

3. MASSES OF DISRUPTED GCS

We estimate the masses of the GCs producing the streams using a simple analytic GC disruption model (Lamers et al. 2005), which reproduces direct N-body simulations of GCs undergoing tidal evaporation in a static background potential (Baumgardt & Makino 2003). Specifically, we obtain a ‘pre-evaporation’ GC mass M_0 by estimating the total mass loss due to stellar evolution and tidal evaporation for a cluster on the inferred orbit over some timescale t . We refrain from deriving an ‘initial’ GC mass, because tidal evaporation in the host galaxy halo is not the only mass loss mechanism experienced by GCs over the course of their history. Prior to being deposited into the halo, GCs were disrupted by tidal shocks due to gravitational perturbations from overdensities in the interstellar medium

of their natal galaxy (e.g. Gieles et al. 2006; Kruijssen et al. 2011; Miholics et al. 2017; Pfeffer et al. 2018). Integrated over the history of GCs, tidal shocks are thought to dominate the total dynamical mass loss (e.g. Kruijssen 2015). Therefore, the quantity M_0 refers strictly to the ‘pre-evaporation’ GC mass – after the first phase of disruption tidal shocks, but before the second phase of disruption by tidal evaporation. We also include the total amount of mass lost by stellar evolution, so that only the mass loss by tidal shocks is unaccounted for.

We relate M_0 to the orbit of the stellar stream by assuming a present-day GC mass of zero (consistent with the fact that only a fossil stream remains) and writing eq. 7 of Lamers et al. (2005) as

$$M_0 = \frac{1}{\mu_{\text{ev}}(t)} \left(\frac{\gamma t}{t_0} \right)^{1/\gamma}. \quad (1)$$

In this expression, $\mu_{\text{ev}}(t)$ is the fraction of the initial GC mass lost by stellar evolution, provided by Lamers et al. (2005) as

$$\mu_{\text{ev}}(t) = 1 - q_{\text{ev}}, \quad (2)$$

with

$$\log_{10} q_{\text{ev}}(t) = [\log_{10}(t/\text{yr}) - a_{\text{ev}}]^{b_{\text{ev}}} + c_{\text{ev}}, \quad (3)$$

and $a_{\text{ev}} = 6.93$, $b_{\text{ev}} = 0.255$, and $c_{\text{ev}} = -1.682$, appropriate for a GC-like metallicity of $0.02Z_{\odot}$ and a Kroupa (2001) stellar initial mass function (Kruijssen & Lamers 2008). The variables γ and t_0 represent the exponent and proportionality factor, respectively, of the Lamers cluster disruption law:

$$\tau_{\text{dis}} = t_0 \left(\frac{M}{M_{\odot}} \right)^{\gamma}, \quad (4)$$

where τ_{dis} is the cluster disruption timescale. We follow Kruijssen & Mieske (2009) in adopting $\gamma = 0.7$ and relating t_0 to the orbital parameters as

$$t_0 = t_{0,\odot} \left(\frac{R_a}{8.5 \text{ kpc}} \right) \left(\frac{v_c}{220 \text{ km s}^{-1}} \right)^{-1} (1 - e), \quad (5)$$

with $t_{0,\odot} = 10.7 \text{ Myr}$ and R_a , v_c , and e denoting the orbital apocenter radius, circular velocity, and orbital

eccentricity, respectively. Finally, we assume that the time spent by each GC orbiting the Milky Way prior to dissolving into a fossil stream is $t = 10 \text{ Gyr}$. This is motivated by the typical ages of GCs in the Galactic halo ($\sim 12 \text{ Gyr}$, e.g. Kruijssen et al. 2019) and by recent results showing that fossil stream lifetimes are much shorter than GC ages (!!REF), such that the progenitors of fossil streams must have disrupted in the past few Gyr. Our results are robust to this choice – an error of 0.3 dex (i.e. a factor of 2) in t translates into an error of just 0.2 dex in the pre-evaporation mass M_0 .

We propagate the uncertainties on the fossil streams’ orbital parameters into those on the pre-evaporation masses by applying eq. (1) to the entire sample of MCMC solutions. The resulting distributions of all apocenter radii, eccentricities, and pre-evaporation masses of the fossil streams in the MCMC sample are shown in Figure 1, where we also include the population statistics of Galactic GCs that have survived till the present day. For these surviving GCs, we also include an estimate of their pre-evaporation masses.

4. DISCUSSION

- summary
- caveats: – orbit fits -> compare to published ones; 5d fits predictive, don’t change much w 6d (ibata) – 10 Gyr disruption time for estimating the mass
- compare to mass estimates in the detect part of the stream -> are they mostly detected or are they extending past the currently detected endpoints?
- lower mass -> implications for epicycles

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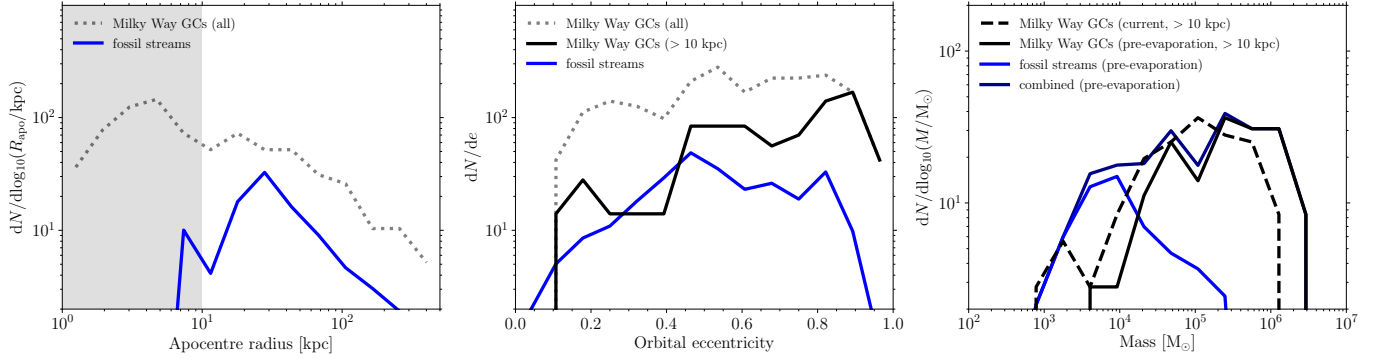


Figure 1. Caption text.

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