176. Black holes in stellar streams

In my previous essay, I noted that recent work has suggested that the existence of stellar mass black holes should have observable consequences on the structure of open clusters and stellar streams. I provided some background to the formation and detection of black holes in interacting and quiescent binaries, then looked at the evidence for such systems in open clusters, and the suggestion that the Hyades possibly contains 2–3 such stellar mass black holes at the present time.

Here I will look at how the existence of stellar mass black holes might affect the morphology and kinematics of the stellar streams that are now known to exist in the inner and outer halo of our Galaxy, and to what extent Gaia can help to distinguish between those that are rich in, or devoid of, stellar mass black holes.

Although the main development that I will report on here – their influence on the structure of the tidal tails of the globular cluster Palomar 5 – is not directly based on Gaia data, the results have benefitted from, and will be more widely applicable to, many of the other stellar streams that Gaia is discovering and characterising.

These developing ideas, still in their infancy, throw light on topics such as the distinction between streams originating from globular clusters or disrupted galaxies, and why some systems being captured by our Galaxy have tidal tails and others do not.

Let me first gather a few key points by way of context, for the story has a number of facets.

The 'hierarchical merger' scenario for our Galaxy, in which it grew through mergers of smaller galaxies, developed from the ideas of Searle & Zinn (1978), and began to take shape with the first observational evidence for halo tidal streams (Majewski et al., 1996), and the discovery of the Sagittarius dwarf galaxy which appears to be in the process of tidal disruption (Ibata et al., 1994).

Today, this picture is supported by improved knowledge of the orbits of the Local Group galaxies, the presence of many more stellar streams, and by the large-scale N-body simulations of ΛCDM cosmology. The pre-Gaia development of the field of stellar streams is nicely detailed by Newberg (2016).

In this process of hierarchical galaxy formation, tidal forces slowly disrupt the accreted systems, forming the tidal tails of extant progenitors, or residual stellar streams, roughly aligned with the progenitor's orbit. Stars near the system's L1 and L2 Lagrange points are lost preferentially, and the differences in orbital frequency between stripped stars and the progenitor produce the leading and trailing tails that grow in extent with time.

Some 100 halo streams are known today, many from Gaia (e.g. Mateu, 2023), some representing the tidal debris of captured dwarf galaxies (where they can be of considerable width, that of Sagittarius being ~6 kpc), with thin streams inferred to be the debris of dissolved globular clusters. Some can be identified as stellar overdensities, others as stars with similar locations and velocities or angular momenta (essays 15, 71, and 156).

Discussions of whether individual progenitors were globular clusters or dwarf galaxies is complicated not least because of the incomplete understanding of the origin and nature of globular clusters, as well as some overlap as well as inconsistencies in their properties.

Simply stated, globular clusters were originally believed to be dense stellar systems which resulted from one generation of stars formed from a single giant molecular cloud (and thus with roughly the same age and metallicity, although the present picture is more complex), and generally considered free of gas and dark matter. Dwarf galaxies contain stars, sometimes gas, and (generally) significant amounts of dark matter.

I will not say more on the complex dynamical processes that occur in globular clusters, which include various mass-loss mechanisms (e.g. Weatherford et al., 2023a; Weatherford et al., 2023b), the dynamical heating of binary stars, mass segregation and, in some cases, 'core collapse' (e.g. Gürkan et al., 2004).

But let me emphasise a key point made in essay 175: that stellar mass black holes must exist in at least some globular clusters (rather than all being ejected), as evidenced by the presence of active X-ray binaries and gravitational wave generating binary mergers, and guided by simulation results (e.g. Morscher et al., 2015).

Of the several dozen *thin* stellar tidal streams now known in the Milky Way halo, none has a known progenitor. But their narrow widths ($\lesssim 100$ pc) imply that their progenitors must have had a small velocity dispersion, suggesting that they originated from dark matter-free globular clusters rather than dwarf galaxies. Streams of width 100 pc or more show an overlap between the two populations (Patrick et al., 2022).

But unambiguously associating these with disrupted globular clusters encounters some problems. One was the finding by de Boer et al. (2020) that the implied mass-loss rate of the GD–1 stream was a factor 4 higher than in early models of cluster evolution (Baumgardt & Makino, 2003). They suggested that their high stellar escape rate could specfically imply low-density progenitors, or the presence of black holes within the globular cluster.

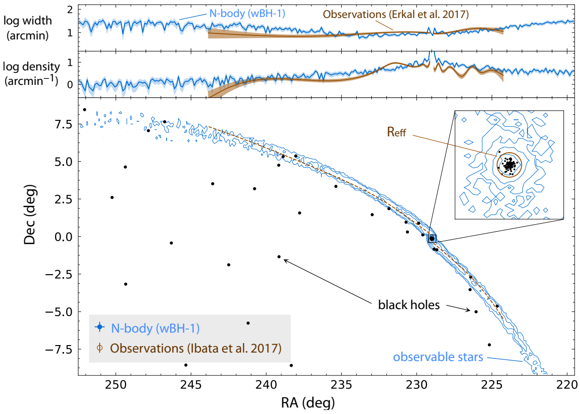
That the presence of black holes provides an abrupt cluster dissolution mechanism was demonstrated in the `MOCCA` N-body simulation of globular clusters by Giersz et al. (2019), who also found that this could lead to a strong increase of black hole and black hole–black hole binaries in the Galactic halo and bulge. Some further implications are detailed by Gieles & Gnedin (2023).

Let me now turn to Palomar 5, a distant (~20 kpc) globular cluster with an unusually low central density and two prominent tidal tails, discovered with SDSS, and extending over more than 2° on the sky (Odenkirchen et al., 2001). More recent studies, some based on Gaia data, have extended knowledge of the spatial extent of these tidal tails to around 30°, and demonstrate how its morphology and kinematics provide constraints on the enclosed Milky Way mass, and on the oblateness of its dark matter halo (essay 109).

For example, Pearson et al. (2015) found that Galaxy potential models which assume a spherical dark matter halo match the observed morphology, while no plausible model could be found in the triaxial potential of Law & Majewski (2010), which had been proposed to explain the properties, and 'fanning', of the Sagittarius stream.

In another pre-Gaia study, Ibata et al. (2017) showed that the paucity of low-mass stars in the cluster itself also extended to the stellar populations along the trailing arm out to 6°, implying that the ejection of the low-mass stars occurred before the formation of the stream.

Most relevant for the subject of this essay, Gieles et al. (2021) used N-body simulations, matched to the cluster members from Erkal et al. (2017), to show that both the cluster's sparseness, and its tidal tails, can be explained by a stellar-mass black hole population comprising 20% of its present mass. Their model corresponds to the presence of 124 black holes with an average mass of $17.2 M_\odot$, currently residing within its half-light radius, $R_{\rm eff}$, of 3.21 arcmin (18.7 pc). Their models followed the cluster for 11.5 Gyr in a three-component Milky Way (bulge, disk, and halo), including the effects of stellar and binary evolution, and with two different prescriptions for the black hole natal kicks.



Gieles et al. (2021)

They concluded that Pal 5 could have formed with a 'normal' black hole mass fraction (of a few per cent). But with stars being lost at a higher rate, the black hole fraction gradually increased, further enhancing tidal stripping and tail formation. They also predicted that Pal 5 will dissolve, in ~1 Gyr, to leave a 'black hole cluster', and suggested that such black hole dominated clusters may be the progenitors of these thin stellar halo streams. Whether clusters evolve towards black hole-free clusters, or 100% black hole clusters depends, they found, on their initial density relative to the tidal density.

They also investigated whether the black hole population could be detected from the cluster's kinematics, along the lines attempted by Wan et al. (2021) for NGC 3201, or from the binary population, and the (limited) prospects of discovering them by microlensing.

Subsequent N-body simulations have suggested that the inclusion of primordial binaries has a noticeable but not drastic effect on the cluster's dynamical evolution, and that observations focussing on the cluster's velocity dispersion, and on binaries with periods of $10^4 - 10^5$ days in its inner and tail regions, will best constrain the black hole existence (Wang et al., 2024).

Further numerical simulations to quantify the differences between streams originating from star clusters with and without black holes have been made by Roberts et al. (2024). They found that, compared to streams from black hole-free clusters, those from black hole-rich clusters are some five times more massive; have a peak density three times closer to the cluster after 1 Gyr; and have narrower peaks and more extended wings in their density profile.

With various caveats, they also concluded that if the tails suggest a progenitor having a high mass-loss rate, the most likely interpretation is that the progenitor was rich in black holes.