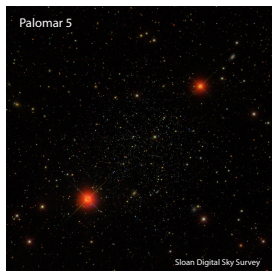

109. The tidal tails of Palomar 5

PALOMAR 5 is one of 15 faint, distant, or obscured globular clusters in the Milky Way, discovered (most for the first time) on the Palomar Sky Survey plates in the early 1950s, in this case by Walter Baade. Some 8 arcmin in extent, with $M \sim 10^4 M_\odot$, it lies some 18 kpc from the Galactic centre, and about 20 kpc from the Sun, more than twice our distance from the Galactic centre.



Palomar 5 generated renewed interest twenty years ago, with the discovery, from the multi-colour Sloan Digital Sky Survey, reaching well below the main sequence turnoff, of two tidal tails, one on each side of the cluster, visible over an arc of 2.6° on the sky (Odenkirchen et al., 2001). Estimating that the tails made up one third of the present cluster stars

in the range $i = 19.5 - 22.0$ mag, they inferred that the cluster is experiencing heavy ongoing mass loss, mainly along a line tracing out the cluster's Galactic orbit.

THE 'BIG PICTURE' TODAY is that all stars form in clusters or associations, which disintegrate over time into the field population. Two-body relaxation leads to the more massive sinking to the central cluster regions, while the less massive gradually escape, or 'evaporate'. Additionally, the Galactic potential perturbs clusters to form tidal tails, an effect observed for both open clusters – amongst them Berkeley 17 (Chen et al., 2004), NGC 6791 (Dalessandro et al., 2015), and the Pleiades (Lodieu et al., 2019) and globular clusters – amongst them Palomar 5, and NGC 5466 (Belokurov et al., 2006).

Today, through its astrometry and photometry, Gaia is enabling the discovery of many more of these low-stellar density tidal tails, including (for open clusters) the Hyades, Coma Ber, Ruprecht 147, M67, and more than a dozen others from Gaia DR2. And Bhattacharya et al. (2022) used Gaia EDR3 to identify 46 open clusters having a stellar corona beyond the tidal radius, 20 of which exhibit extended tails aligned with the cluster orbit around the Galaxy.

THE FORMATION and origin of *globular* clusters remains imperfectly understood, although their large age and low metallicity point to them being relics of our Galaxy's formation. Their stars are believed to have originated in regions of more efficient star formation and/or higher density regions of the interstellar medium, while those far out in the halo, and in particular those with retrograde orbits, likely formed in dwarf galaxies which were later gravitationally captured by the Milky Way.

The tidal streams in the vicinity of known globular clusters, including Palomar 5, are believed to be closely related to the thin stellar streams being discovered in our Galaxy's halo by Gaia today (see essay #15 on Enceladus, and #71 for several others) in which the original dense cluster cores have presumably all but evaporated.

Studies of halo streams aim for an improved understanding of our Galaxy's formation through the accretion of satellite galaxies over cosmological time scales.

Studies of the tidal tails of open and globular clusters target an improved understanding of escape mechanisms and, in the case of globular clusters, the mass, shape, and even substructure of the dark matter distribution in the Galaxy, and especially of its halo.

FURTHER by way of introduction, I will mention that stars can escape from clusters through various mechanisms (Binney & Tremaine 2008, §7.5.6; Weatherford et al., 2002). *Ejection* mechanisms, in which a single impulse event substantially increases the velocity of a cluster member, include strong gravitational encounters and recoil kicks from stellar evolution, supernovae, and tidal disruption events. *Evaporation* mechanisms, operating on much longer time scales, include two-body relaxation and tidal stripping. The strongest tidal shocks on globular clusters in our own Galaxy are generated as the cluster crosses the Galactic disk or passes through pericentre on a highly eccentric orbit.

For Palomar 5, Odenkirchen et al. (2001) used the cluster's estimated proper motion, of $\sim 2 \text{ mas yr}^{-1}$ in RA and dec, to predict its next passage through the Galactic disk in ~ 100 Myr, producing a strong tidal shock that may eventually dissolve the cluster completely.

DESPITE limited data on its kinematics, Palomar 5 is viewed as a canonical example of tidal destruction, and a useful probe for constraining Galactic structure. Using deep photometry, the density variations along the stream have been used to place limits on the abundance of massive substructures in the Galactic halo (Erkal et al. 2017). And using the sky path and radial velocity information, the stream has been used to measure the enclosed mass of the Milky Way (Dai et al. 2018).

N-body simulations have shown that both the cluster's sparseness, and its tidal tails, can be explained by a stellar-mass black hole population comprising 20% of the its present mass (Gieles et al. 2021). It 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.

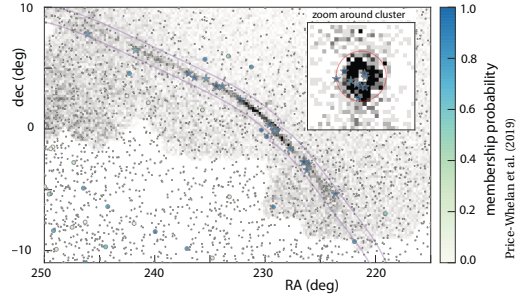
Gieles et al. (2021) predict that the cluster will dissolve, in ~ 1 Gyr, to leave a black hole cluster. Black hole-dominated, extended clusters may therefore, they conclude, be the progenitors of the thin stellar streams being discovered in the Galaxy halo.

PALOMAR 5 is too distant for useful membership selection based on ground-based proper motions. Accordingly, some of the latest studies have used deep photometry, including from the DECam Legacy Survey (Bonaca et al. 2020) and the Dark Energy Spectroscopic Instrument (Xu et al. 2021). These and other photometric surveys have extended the total length of the known tails to some 20° (over 4° for the leading arm, and 15° for the trailing), provided evidence of 'fanning' in the leading arm, and led to improved estimates of the cluster's core radius (~ 3 arcmin), tidal radius (~ 18 arcmin), and of its metallicity ($[\text{Fe}/\text{H}] = -1.798 \pm 0.014$), distance (23.28 ± 0.05 kpc), and age (11.50 ± 0.03 Gyr).

GIVEN THAT more detailed models require improved membership certainty, and an improved knowledge of their individual positions and space motions, let me now turn to the most recent insights from Gaia.

Although the cluster's main sequence is only just accessible with Gaia DR2, its horizontal branch is bright enough, at $G \sim 17.3$, to provide the first precise proper motions along the full extent of the tidal stream. Accordingly, Price-Whelan et al. (2019) used RR Lyrae stars (pulsating horizontal branch giants), as standard candles, to determine improved distances and kinematics.

They identified 10 RR Lyrae as cluster members, and a further 17 as members of the stream (figure below). They gave a revised distance of $d = 20.6 \pm 0.2$ kpc, and detected gradients in distance (of 0.2 kpc per degree), and proper motion, along the stream. These were consistent with the simulations of Pearson et al. (2017) which, by including the rotating Galactic bar, also reproduced the observed truncation of the leading arm.



ANOTHER detailed search for members of the tidal tails was made, with Gaia DR2, by Starkman et al. (2020). As exploited in recent stream-search algorithms, the extensive astrometric data permits more restrictive phase-space limits, despite the fact that the Gaia DR2 photometry is not competitively deep. They extended the arc length to 30° , of which 7° were new detections along the leading arm, resulting in leading and trailing arms which are symmetric in length and near constant in width. . . and a new constraint for models in which the Galactic bar truncates the cluster's leading arm.

FURTHER STUDIES exploiting the Gaia EDR3 astrometry by Kuzma et al. (2022) selected two fields along the leading tail observed with the AAT-AAOmega spectrograph. One of the fields lies roughly 7° along the leading tail, beyond the regions that had been explored spectroscopically previously.

Combining their kinematics and line strengths with Pan-STARRS1 photometry and Gaia EDR3 astrometry, they identified 16 new stars belonging to the Palomar 5 stream, yielding 109 cluster/tidal stream stars in total. Eight lie in the outermost field, with their sky positions confirming the presence of 'fanning' in the leading arm.

AMONGST the latest simulations, Palau & Miralda-Escudé (2022) modelled the oblateness of the Milky Way dark matter halo from fits to the Palomar 5 stellar stream, along with two other globular cluster streams: NGC 3201 and NGC 4590 (M68). The Palomar 5 stream constrains the halo to be close to spherical. The stream of M68 is consistent with a spherical halo, but favours a prolate configuration. The three together are well fitted with a halo axis ratio $q = 1.06 \pm 0.06$, and core radius ~ 20 kpc. While their halo oblateness agrees with previous studies using other observational data, it is in tension with cosmological simulations predicting that most spiral galaxies have oblate dark matter halos with the short axis perpendicular to the disk.

GAIA-BASED studies of halo streams and tidal tails are still in their infancy. With the tails being sensitive to the shape of the Galactic halo, and with longer tails being more constraining, Dai et al. (2018) have argued that Gaia should provide '*... decisive tests of the consistency between Λ CDM and Milky Way streams*'.