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The Extended Tidal Tails of Palomar 5: Tracers of the Galactic Potential

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Abstract. We detected extended, curved stellar tidal tails emanating from the sparse, disrupting halo globular cluster Pal 5, which cover 10° on the sky. These streams allow us to infer the orbit of Pal 5 and to ultimately constrain the Galactic potential at its location.

1. Palomar 5: A Globular Cluster Torn Apart by the Milky Way

Palomar 5 is an extraordinarily sparse globular cluster in the outer halo of the Milky Way, at a distance of 23 kpc from the Sun (Fig.1). Its peculiar properties (e.g., very low mass, large core, relatively flat luminosity function) fostered the idea that this cluster might be a likely victim of disruptive Galactic tides.

Using deep multi-color photometry from the Sloan Digital Sky Survey (SDSS; York et al. 2000, Gunn et al. 1998) we found unambiguous, direct evidence for the suspected tidal disruption of Pal5 (Odenkirchen et al. 2001; Rockosi et al. 2002): For the first time, two massive tails of stellar debris with well-defined S-shape geometry were detected, emanating in opposite directions from the cluster.

As the SDSS is scanning more and more of the sky we have now extended our search over an area of ~ 87 deg². Contaminating objects were removed by eliminating extended sources and by applying an optimized smooth color-magnitude-dependent weighting function. This optimized weighting enhances the density contrast between cluster and field stars by almost a factor of 20 and provides a least-squares solution for the spatial distribution of the cluster population. The resulting surface density map of Pal5 stars is shown in Fig. 2.

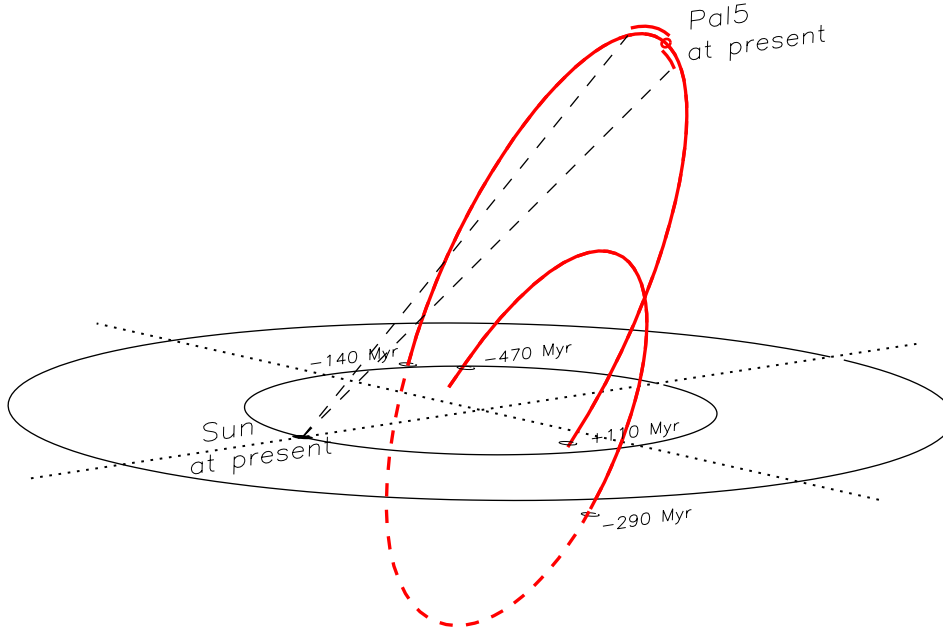


Figure 1. The present location of Palomar 5 in the Milky Way and its inferred plunging Galactic orbit (fat solid and dashed line). The approximate times of past and future disk passages are indicated.

2. A Narrow, Curved, 10 Degree Stream of Debris

We find that the tidal tails extend over an arc of at least 10° on the sky and form a narrow stream with a FWHM of only $18'$. This corresponds to a projected length of $\simeq 4$ kpc in space, and a projected FWHM of 120 pc. The northern tail is visible out to 6.5° from the cluster. The southern tail is traced over 3.5° but probably continues beyond the border of the currently available field (Fig. 2). The stellar mass in the tails adds up to 1.2 times the mass of stars in the cluster, i.e., the tails contain more mass than what is left in the cluster. Pal5 thus presents a text-book example of a tidally disrupting globular cluster. It is so far the only known stellar system besides the Sagittarius dwarf galaxy that demonstrates the formation of a halo stream within the Milky Way.

The tails have a clumpy structure (Fig. 2). This implies that the mass loss has been episodic, and suggests that it was triggered by disk and/or bulge shocks. Indeed Pal5 passes through the Galactic disks at intervals of a few 100 Myr (Fig. 1). In Fig. 3 we present the radial profile of the stellar surface density (i.e., the azimuthally averaged surface density as a function of distance from the cluster center) from the core of the cluster out to the current end points of the tails. The profile shows a characteristic break near the cluster's tidal radius at about $16'$. Inside this radius, the profile decreases approximately like r^{-3} . Beyond this limit the profile is flatter and approximately follows an $r^{-1.5}$ power law. The overall decrease thus differs from a simple r^{-1} power law that would result from a constant linear density along the tails.

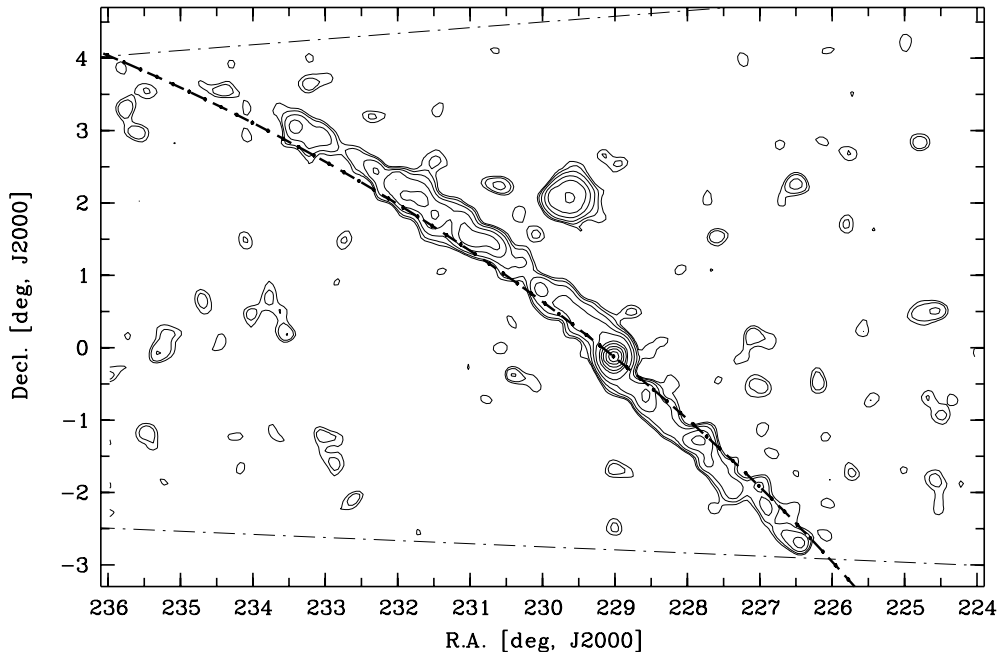


Figure 2. Contour map of the surface density of Pal 5 stars derived by weighted star counts of SDSS point sources. The fat dashed line shows the best-fit local orbit of the cluster. The curved dash-dotted lines indicate the border of the current SDSS scan region.

3. Clues on the Cluster's Orbit and Mass Loss Rate

Location and curvature of the tails are direct tracers of the cluster's Galactic motion and hence provide unique information about the orbit of Pal 5. The best-fit local orbit is shown as dashed line in Fig. 2. The direction of the cluster's motion is determined by its orientation with respect to the Galactic center: The southern, leading tail and the northern, trailing tail indicate that Pal 5 is on a prograde orbit. Using a standard three-component model for the Galactic potential we infer that Pal 5 is observed close to the tails' maximum distance from the Galactic disk and has recently passed through apogalacticon (implying that the tidal stream is currently relatively dense). In about 100 Myr the cluster will cross the disk at a distance of only 7 kpc from the Galactic center (see Fig. 1). This will produce a strong tidal shock that might lead to complete disruption.

The amount by which the tails are offset from the orbit of the cluster is directly related to the velocity at which the tidal debris drifts away from the cluster. The observed mean offset (about 75 pc in projection), the parameters of our model orbit, and the total amount of stellar mass seen in the tails lead to an estimate of the mean mass loss rate of about $5 M_{\odot} \text{ Myr}^{-1}$. Assuming this rate to be more or less constant (as suggested by numerical simulations) we conclude that 10 Gyr ago Pal 5 may have had a mass of about $5 \cdot 10^4 M_{\odot}$. This is about ten times as much as it has today, but still considerably less than the mass of an average present-day Galactic globular cluster.

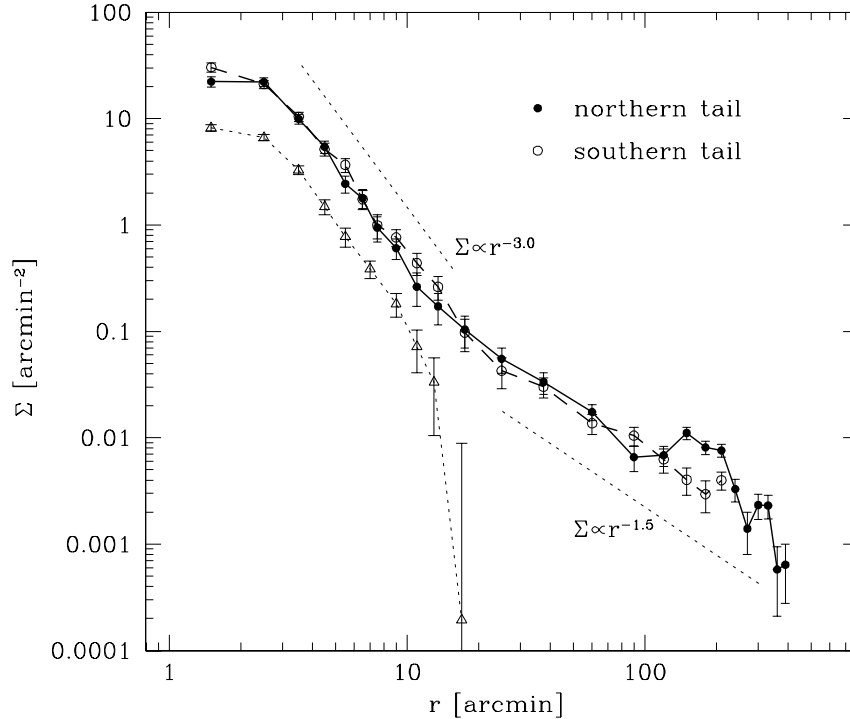


Figure 3. Radial profile of the stellar surface density in the cluster and tails from number counts in sectors of concentric rings. For comparison the leftmost data points show the cluster profile from counts in sectors perpendicular to the tails (arbitrarily shifted by -1 in $\log \Sigma$).

The current data allow us to predict the tangential velocity of Pal 5 as a function of the parameters of the Galactic potential. GAIA and SIM will allow us to accurately measure the velocities and proper motions of stars in the cluster and in the extended tails, fully characterizing the kinematics of the stream independent of any galactic model. In return, these kinematics impose strong constraints on the Galactic potential at the location of the cluster.

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