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Letter to the Editor

Hyades tidal tails revealed by *Gaia* DR2⋆,⋆⋆

Siegfried Röser[1,2], Elena Schilbach[1,2], and Bertrand Goldman[3,4]

[1] Zentrum für Astronomie der Universität Heidelberg, Landessternwarte, Königstuhl 12, 69117 Heidelberg, Germany
[2] Zentrum für Astronomie der Universität Heidelberg, Astronomisches Rechen-Institut, Mönchhofstraße 12-14, 69120 Heidelberg, Germany
e-mail: roeser@ari.uni-heidelberg.de, elena@ari.uni-heidelberg.de
[3] Max-Planck-Institut für Astronomie, Königstuhl 17, 69117 Heidelberg, Germany
e-mail: goldman@mpia.de
[4] Observatoire Astronomique de Strasbourg, Université de Strasbourg – CNRS UMR 7550, 11 rue de l'Université, 67000 Strasbourg, France

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ABSTRACT

Aims. Within a 200 pc sphere around the Sun, we search for the Hyades tidal tails in the *Gaia* DR2 dataset.
Methods. We used a modified convergent-point method to search for stars with space velocities close to the space velocity of the Hyades cluster.
Results. We find a clear indication for the existence of the Hyades tidal tails, a leading tail extending up to 170 pc from the centre of the Hyades with 292 stars (36 contaminants), and a trailing tail up to 70 pc with 237 stars (32 contaminants). A comparison with an N-body model of the cluster and its tails shows remarkably good coincidence. Five white dwarfs are found in the tails.

Key words. parallaxes – proper motions – open clusters and associations: general – open clusters and associations: individual: Hyades

1. Introduction

The Milky Way galaxy exerts tidal forces onto its gravitationally bound stellar sub-systems with the effect that these sub-systems continuously lose members. Once the members are no longer gravitationally bound, they might still remain in co-moving tidal tails that lead and trail their home sub-system. The tidal tails of stellar clusters are an important piece of information on the clusters' kinematic evolution, the process of dissolution, and the impact of the Galactic gravitational field onto a sub-system. Thus far, only tidal tails of massive clusters and dwarf galaxies have been discovered in the Milky Way system. Probably the most famous of these are the tidal tails of the globular cluster Palomar 5 (Pal 5) detected by Odenkirchen et al. (2001). The tails of Pal 5 can be traced over an arc of at least 22° on the sky (Grillmair & Dionatos 2006; Ibata et al. 2016). Tidal tails around open clusters in the Milky Way are also expected, but have not yet been detected. They are thought to be much less prominent than the tails of globular clusters such as Pal 5 and are more difficult to detect. The reason for this is that open clusters mainly reside close to the Galactic plane and are surrounded by a high background of field stars. In addition, possible collisions with massive molecular clouds can destroy parts of the tails (Gieles et al. 2006).

The Hyades cluster is the nearest open cluster in the solar neighbourhood and is richly populated. The distance of the centre of the Hyades from the Sun is only 46.75 ± 0.46 pc (Gaia Collaboration 2017) according to *Gaia* DR1, or 47.50 ± 0.15 pc (Gaia Collaboration 2018a) according to *Gaia* DR2. This proximity has made it a most interesting target for centuries, and a Simbad query on "Hyades" resulted in 2472 references between 1900 and 2018. Röser et al. (2011) found 724 stars to be co-moving with the mean Hyades space velocity, representing a total mass of 435 $M_{\odot}$. The authors determined a tidal radius of about 9 pc, and 364 stars (275 $M_{\odot}$) are gravitationally bound. Goldman et al. (2013) extended this search to lower masses using PanSTARRS1 photometry, down to 0.1 $M_{\odot}$. Using Hipparcos observations, Perryman et al. (1998) determined the isochronic age of the Hyades to be 625 ± 50 Myr. Recently, Martín et al. (2018) derived an age of 650 ± 70 Myr using the lithium-depletion-boundary method, and Gossage et al. (2018) found 680 Myr from MESA stellar evolutionary models including rotation. Using a Bayesian colour-magnitude dating technique including rotating stellar models, Brandt & Huang (2015) derived a different age for the Hyades of ≈800 Myr.

Kharchenko et al. (2009) studied the observed and modelled shape parameters (apparent ellipticity and orientation of the ellipse) of 650 Galactic open clusters in the solar neighbourhood. In the course of this study, they performed N-body simulations to follow the evolution of a model open cluster,

⋆ We acknowledge the simultaneous publication by Meingast & Alves (2019), who also used *Gaia* DR2 to present evidence for the existence of the Hyades's tidal tails. The authors of both publications did not know about each other's work and arrived at their conclusions independently.
⋆⋆ The data of all 1316 stars from Fig. 3 are only available at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via http://cdsarc.u-strasbg.fr/viz-bin/qcat?J/A+A/621/L2

originally spheroidal, with an initial mass of 1000 $M_\odot$ and the Salpeter initial mass function (IMF) down to 0.1 $M_\odot$. This model cluster moves on a circular orbit in the external tidal field of the Milky Way and is located close to the observed current location of the Hyades (for more details of the model parameters, see Kharchenko et al. 2009). It is appropriate to note that the cluster has not been specifically tailored to fit the Hyades, but it is a general model for the evolution of a prototype open cluster in the disc at a Galacto-centric radius of 8.5 kpc. At a cluster age of 650 Myr, these N-body calculations predicted two tidal tails extending up to ca. 700 pc from the centre of the cluster along its orbit around the Galactic centre.

In this paper, we report on the detection of the Hyades tidal tails. The paper is structured as follows: In Sect. 2 we describe the steps we took to find the Hyades tidal tails. Section 2 is divided into subsections describing the astrometric and photometric cleaning, the first detection of the tails after a velocity cut, the cleaning from field stars, and the estimation of contamination. The short Sect. 3 compares observation with the Kharchenko et al. (2009) model, and a summary concludes the paper.

2. Finding the Hyades tidal tails

According to N-body simulations, a Galactic open cluster, initialised as a spheroid, elongates with time along its Galacto-centric radius and begins to lose members, mainly low-mass stars that form two tidal tails along the cluster orbit (Kharchenko et al. 2009). In the N-body models by Ernst et al. (2011), tailored to fit the present-day situation of the Hyades, these tidal tails would reach a length of about 800 pc if they had not been destroyed in the last 650 Myr by passing molecular clouds, disc shocking, spiral arm passages, and other events not taken into account by the model. In the vicinity of a cluster, tails reveal themselves as co-moving stars with space velocities close to the velocity of this cluster. With increasing distance from the cluster centre, the space velocities of former cluster members can, however, differ significantly from the velocity of the cluster itself (see, e.g. Chumak et al. 2010). Therefore, we focused our search on a smaller volume and chose a sphere around the Sun with a radius of 200 pc. This should be large enough to contain a good portion of the Hyades tails if they still exist.

In the following discussion we use barycentric Galactic Cartesian coordinates X, Y, Z. We followed the *Gaia* catalogue convention, and the axes X, Y, Z are directed to the Galactic centre, the direction of Galactic rotation, and to the Galactic north pole, respectively. The corresponding velocity coordinates are U, V, W. For the central part of the Hyades, we determined the phase space coordinates on the basis of positions, proper motions, parallaxes, and radial velocities from *Gaia* DR2 and information on membership from Gaia Collaboration (2018a). We found mean values of

$$\begin{aligned} \boldsymbol{R}_c = (X_c, Y_c, Z_c) &= (-44.77, +0.40, -16.24)\,\text{pc}, \\ \boldsymbol{V}_c = (U_c, V_c, W_c) &= (-42.24, -19.00, -1.48)\,\text{km}\,\text{s}^{-1}. \end{aligned} \quad (1)$$

These values are almost identical to the previous determination by Reino et al. (2018) based on *Gaia* DR1.

2.1. Preparatory work

From the *Gaia* DR2 dataset (Gaia Collaboration 2018b) we extracted all entries with a parallax greater than 5 mas, which gave some six million objects. For the further processing, we followed the procedures described in Gaia Collaboration (2018c), Sect. 4.3 and Appendix C, Figs. C.1 and C.2, to obtain a stellar sample cleaned from possible artefacts.

First we applied the “unit weight error” cut (cf. Eq. (C.1) in Gaia Collaboration 2018c), which removed a considerable portion of dubious entries, and 3.6 million sources remained. As a next step, we applied the “flux excess ratio” cut and followed here the procedure given in Gaia Collaboration (2018a), which reduced the sample to 1 461 162 objects. To exclude dubious measurements, we discarded all stars with relative errors of parallax larger than 10 percent. This forms an astrometrically and photometrically clean sample of 1 452 246 stars. The distributions of their G and M_G magnitudes show maxima at 17 mag and 12 mag, respectively. The price for this cleaning therefore is some incompleteness at the faint end.

2.2. Constraining the velocity space

In the ideal case, we need observed space velocities for each star in a sample to identify stars co-moving with the Hyades. However, measured radial velocities are lacking for the vast majority of stars. Therefore we had to rely on criteria that are solely based on their tangential velocities. This implies that we may detect stars that are highly probable co-moving, although they need final confirmation when the radial velocities are measured. We followed the formalism of the convergent-point (CP) method as described in van Leeuwen (2009), for instance, and transformed the Cartesian velocity vector of the cluster motion $\boldsymbol{V}_c$ from Eq. (1) to give predicted velocities $V_{\|\text{pred}}$ and $V_{\perp\text{pred}}$ parallel and perpendicular to the CP for each star depending on its position on the sky. We note that $V_{\perp\text{pred}} \equiv 0$. Also following van Leeuwen (2009), we similarly transformed the measured (observed) tangential velocities for each star, $\kappa\mu_{\alpha*}/\varpi$ and $\kappa\mu_\delta/\varpi$ into $V_{\|\text{obs}}$ and $V_{\perp\text{obs}}$. Here ϖ is the measured trigonometric parallax in *Gaia* DR2 and $\kappa = 4.74047$ is the transformation factor from 1 mas yr^{-1} at 1 kpc to 1 km s^{-1}. We also determined the covariance matrix for the velocities $V_{\|\text{obs}}$ and $V_{\perp\text{obs}}$ according to error propagation from the covariance matrix of the $\mu_{\alpha*}, \mu_\delta$, and ϖ.

To increase the density contrast in the map of the stellar distribution in the tangential velocity plane, we momentarily constrained the volume around the Hyades within we searched for the tails. We performed cuts as $|Z-Z_c| \leq 20$ pc and $|X-X_c| \leq 100$ pc, where X_c and Z_c are the coordinates of the centre of the Hyades cluster given in Eq. (1). These cuts are ample compared to the predicted extent of the model tails, and they reduced the sample to 154 389 stars. In Fig. 1 we show the distribution of $V_{\|\text{obs}} - V_{\|\text{pred}}$ and $V_{\perp\text{obs}}$ for volume-restricted sample above. When the space velocity of a star is identical to $\boldsymbol{V}_c$ from Eq. (1), the differences between the predicted and observed velocities ($V_{\|\text{obs}} - V_{\|\text{pred}}$, $V_{\perp\text{obs}}$) must be equal to (0,0). The strong maximum at (0,0) in Fig. 1 is definitely caused by the stars of the Hyades cluster proper. A clear over-density also extends along the x-axis in this plot. To extract the co-moving stars from this over-density, we cut out an area between −5 and +3 km s^{-1} in $V_{\|\text{obs}} - V_{\|\text{pred}}$ and −0.8 and +1.1 km s^{-1} in $V_{\perp\text{obs}}$ from Fig. 1. We show the spatial distribution of the 1580 co-moving stars from these cuts as a projection onto the Galactic plane in Fig. 2 (left). The most prominent feature is a strong over-density at the position of the Hyades cluster proper at $Y, X = (+0.40$ pc, -44.77 pc). The cluster shows an elongated shape, indicating that it loses members through the Lagrangian points. Moreover, we observe a weaker but significant over-density extending from the Hyades centre towards $Y, X = (+190$ pc, -22 pc), which can be attributed

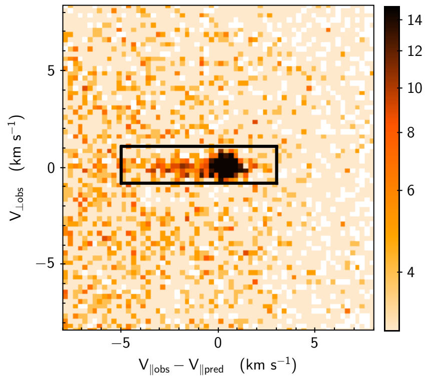

Fig. 1. Velocity distribution of the stars in the tangential velocity plane ($V_{\|\mathrm{obs}} - V_{\|\mathrm{pred}}$, $V_{\perp\mathrm{obs}}$). The zero-point is the predicted value from the space motion of the Hyades. The x-axis points in the direction of the convergent point. The units on the colour-bar are stars per $(0.25\,\mathrm{km\,s^{-1}})^2$. The box indicates the selection window that might belong to the tails.

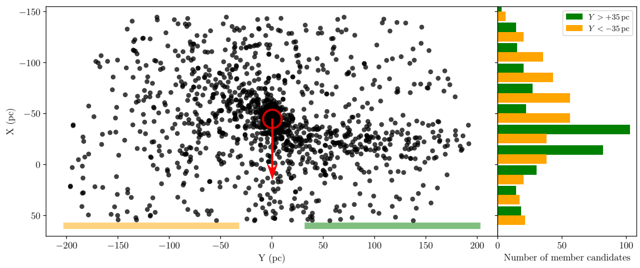

Fig. 2. Left: distribution of the stars in the Y, X-plane after the cut in the tangential velocity plane according to the situation in Fig. 1, described in Sect. 2.2. The red circle indicates the tidal radius of 9 pc, and the red arrow points to the Galactic centre. Right: histogram of the marginal distribution in X; green shows the histogram for $Y > 35$ pc, and yellow represents $Y < -35$ pc.

to the leading tidal tail of the Hyades. The beginning of the trailing tail can be spotted in the direction to $Y, X = (-40\,\mathrm{pc}, -70\,\mathrm{pc})$ from the cluster centre. The over-densities related to the leading and trailing tails can be clearly seen in Fig. 2 (right), where we show the histogram of the marginal distribution in X of stars for $Y < -35$ pc and $Y > 35$ pc (avoiding the cluster itself). The peak at $X = -30$ is due to the leading tail, and the shallower peak at $X \approx -55$ pc is due to the trailing tail. However, there is still a noticeable amount of contamination in Fig. 2. This is due to a rather generous cut in the tangential velocities, which allows an increasing number of co-moving field stars to enter the sample. Nevertheless, we need such a large velocity window to identify the tails since the velocities of the tail stars can differ from the Hyades velocity. Stars outside this velocity range are not considered to adhere to the Hyades tails, at least in the context of this paper.

2.3. Identifying the tidal tails

In order to distinguish the tails from the background, we have to estimate and reduce the influence of isolated field stars that by chance obey the velocity restrictions in $V_{\|\mathrm{obs}}$ and $V_{\perp\mathrm{obs}}$. In the following, we ignored the volume cuts from the previous section and selected now all stars within the sphere of 200 pc around the Sun that fulfilled the velocity restriction (6895 stars). This returned an average stellar density of 0.205×10^{-3} stars per pc^3. We enclosed the sphere by 33 500 cubes with edge lengths of 10 pc to determine the dependence of the contaminating stellar density as a function of the Z coordinate. If all stars were randomly distributed (which is not the case because in particular, the Hyades cluster resides in this volume), we would find from Poisson statistics that only 2 of these cubes should be filled with 4 or more stars. To determine the average contamination by field stars, we therefore disregarded all cubes with 4 or more stars. These presumably contain a non-field star component. The field star density at a given grid point Z is taken as the average over all cubes at this Z. We found a maximum density at the grid point with $Z = -10$ pc with a value of 0.358×10^{-3} stars per pc^3. The density decreases for higher and lower Z and falls below the mean of 0.205 at $Z = -50$ pc and $Z = +50$ pc. For each cube, we then calculated the probability $p(Z)$ that at least one field star from a random distribution lies in this cube. For a star in a given cube filled with N stars, we attached an individual value of $p(Z)/N$ as contamination. We did this for all 6895 stars. This procedure enabled us to estimate the number of contaminating field stars in the Hyades cluster itself and its possible tails. This is only a statistical contamination, individual stars cannot be spotted as contaminants.

The sub-division of the 200 pc sphere gave rigorous fixed cuts between adjacent cubes regardless of the actual over-densities. Gradients in a distribution are not well represented, as stars at the edges may fall into an (empty) neighbouring cube. To extract physical over-densities, we therefore proceeded as follows: around each of the 6895 stars, we drew a sphere with radius 10 pc and counted the stars that fell into this sphere. We selected spheres that were filled by 6 stars or more, corresponding to a minimum density of 1.5×10^{-3} stars per pc^3, and finally selected all stars that belong to at least one of these spheres (1316 stars). The result of this selection is shown in Fig. 3. We separated different over-densities of co-moving stars shown by different colours in this figure. As the central part of the Hyades, we chose a sphere with radius 18 pc around the centre (corresponding to two tidal radii as determined by Röser et al. 2011). In this volume we found 501 stars (shown as red dots in Fig. 3) with a contamination of 7. The tails were selected by eye as a coherent volume in 3D space that is connected with the cluster at its 18 pc border. Stars in the leading tail of the Hyades are shown as green dots in Fig. 3. The leading tail is a rather homogeneous structure extending up to 170 pc in the positive Y-direction. We counted 292 stars in this tail with a contamination of 36. Blue dots in Fig. 3 mark stars that we assigned to the trailing tail. Here we exceptionally included 6 candidates at $(X, Y, Z) = (-65, -125, -27)$ pc, although they are separated from the coherent part, but they are consistent with the model (see below). The trailing tail looks rather shredded and seems to be in the course of being destroyed. In the trailing tail, we found 237 stars with a contamination of 32. As the trailing tail has such an inhomogeneous structure, we might have chosen some stars that do not originate in the Hyades cluster itself. All other stars in this figure are shown as pink dots and represent minor over-densities of co-moving stars falling in the same tangential velocity box as the Hyades itself, but that are so far away in space from the Hyades that they probably have nothing to do with the cluster. The most prominent feature is a group of 93 stars centred at $X, Y, Z = (140\,\mathrm{pc}, -5\,\mathrm{pc}, -20\,\mathrm{pc})$ in the constellations Sagittarius and Corona Australis, that is, some 150 pc away from the Sun in the direction to the Galactic centre. The colour-absolute-magnitude diagram (CAMD) showed that one half of these stars are young (younger than 100 Myr), and the other half is of the Hyades age or older.

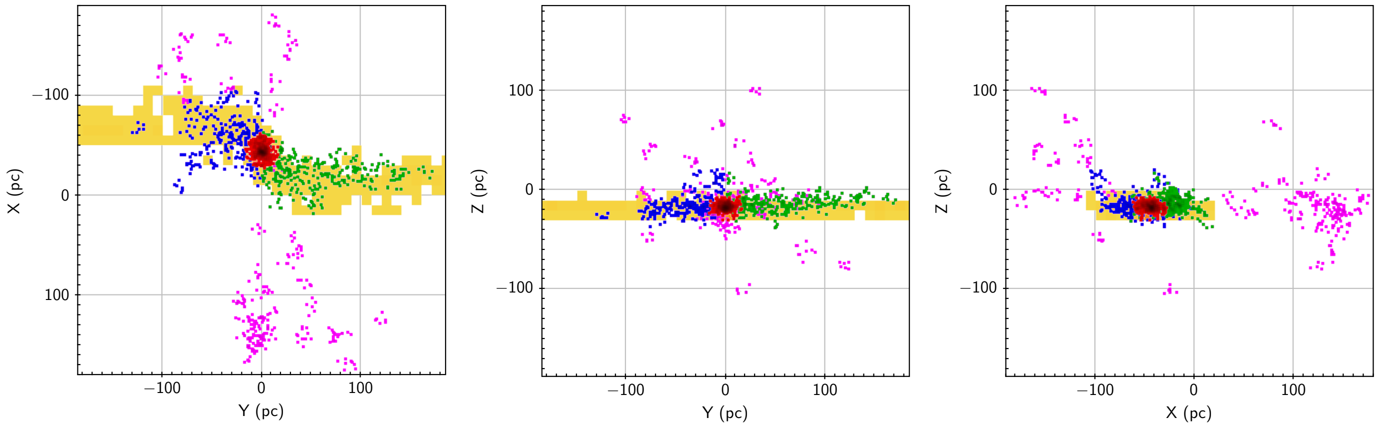

Fig. 3. Hyades and their tidal tails. The figures show the spatial distributions of stars in dense regions with at least 2.5×10^{-3} stars per pc^3 (see text for a further explanation of this selection). *From left to right panels*: distribution in the Y, X-, Y, Z-, and X, Z-planes. Stars selected in *Gaia* DR2 are shown as dots. In red we plot the Hyades cluster proper, in green the leading tail, in blue the trailing tail, and in pink all other stars in dense regions. The location of the predicted Hyades tidal tails from the model by Kharchenko et al. (2009) are indicated in yellow in the background.

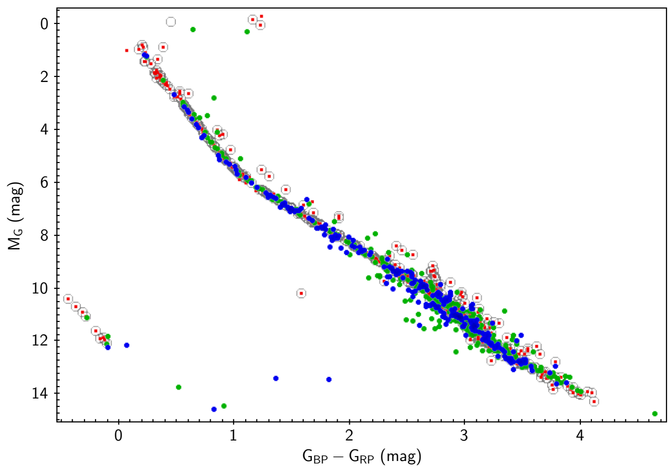

Fig. 4. M_G vs. $G_{\rm BP}-G_{\rm RP}$ CAMD of the Hyades and their tidal tails. The grey circles are the stars by Gaia Collaboration (2018a), representing the cluster proper. The cluster stars selected here are shown as small red dots, and are mostly identical with the Babusiaux stars. The green dots are stars from the leading tail, and the blue dots show stars from the trailing tail.

2.4. Colour-absolute-magnitude diagram

Gaia Collaboration (2018a) published a sample of 515 Hyades members, out of which we found 466 in our sample of 1.5 million stars after the Lindegren cuts. These stars show a sharp and clean empirical cluster sequence in the CAMD M_G versus $G_{\rm BP}-G_{\rm RP}$, which we show in Fig. 4. In this figure the Hyades stars from Gaia Collaboration (2018a) are displayed as grey circles, and the 501 stars selected in the previous section as adhering to the cluster itself are shown as small red dots. The two sequences are identical (small difference in number) and represent the empirical Hyades main sequence. Stars in the tails (blue and green dots) are plotted on top of the cluster stars to indicate that they are mostly consistent with the Hyades stellar population. We found 51 tail stars below the empirical sequence, that is, with older ages or different chemistry. These can be regarded as a subset of the 68 contaminants evaluated above, and in these cases, we can even identify individual stars as contaminants. Five stars in the CAMD are located at the white dwarf sequence ($M_G < 12.5$ mag), three in the leading, and two in the trailing tail. In the leading tail, two have previously been confirmed as white dwarfs; the two in the trailing tail are a pair with separation of about 1 pc, *Gaia* DR2 3308556160422149 12 and *Gaia* DR2 3308556160422181 12. All may have been former Hyades members.

3. Comparison between model and observations

Unfortunately, from the model by Ernst et al. (2011), which is customized to fit the Hyades cluster as described in Röser et al. (2011), we do not possess a dataset representing the simulated tails. However, from the model of Kharchenko et al. (2009), we kept a file giving data of the 4000 simulated stars at a time of 650 Myr. Together with the observations in Fig. 3, we also show the distribution of the simulated stars as a density plot in the background. We find a remarkable concordance between the shapes of the model distribution and the observations, especially with regard to the leading tail. The trailing tail in observations is less pronounced in the area with $Y_{\rm gal} < -80$ pc. We can only speculate that it may have been shredded by shocks or collisions with clouds in the past 650 Myr.

4. Summary

Using the data from *Gaia* DR2, we searched for the presence of Hyades tidal tails in a sphere of 200 pc radius around the Sun. First, the *Gaia* DR2 data were cleaned according to the recipes given in Gaia Collaboration (2018a, 2018c) to obtain an astrometrically and photometrically clean sample. Then, a selection window of only 8 km s^{-1} by 2 km s^{-1} in velocity space was found to be adequate to separate the tails from the vast majority of field stars, at least within our 200 pc sphere. We found 501 cluster members within two tidal radii (18 pc) from the cluster centre with a possible field star contamination of 7, a leading tidal tail extending up to 170 pc in the direction of Galactic rotation with 292 stars and 36 contaminants, and a trailing tail up to 70 pc from the centre of the cluster with 237 stars and 32 contaminants. The latter appears to be shredded. The cluster sequence and the tail sequences in the CAMD are in good coincidence, and the excellent quality of *Gaia* photometry allowed us to identify 51 stars below the cluster sequence proper, which have older ages and/or a different chemistry. They can be considered part of the 69 contaminants. A comparison with a theoretical model for the Hyades tidal tails from N-body calculations (Kharchenko et al. 2009) showed very good coincidence, especially in the case of the leading tail. This is a very satisfactory confirmation for both theory and observations. Five white dwarfs are found in the tails. Serendipitously, we found a moving group, some 150 pc from the Sun near the border between the constellations Sagittarius and Corona Australis. We publish the data of all 1316 stars from Fig. 3 as online material.

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