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Identifying Candidate Moving Groups in the Gaia Catalog

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ABSTRACT

Gaia is a European satellite mission recording positional and radial velocity measurements for about a billion stars in order to create a three-dimensional map of the Milky Way Galaxy. Stars form in groups within giant molecular clouds of gas and dust and are gravitationally bound in what is known as open clusters. The members of an individual cluster share similar kinematic properties as the cluster orbits the Galactic center. Over time open clusters dissolve due to the equipartition process, or disruption from tidal encounters; however the former members still share common motions despite being spread out across the Galaxy. Dismantled members from a given cluster are collectively known as a moving group. Using the Python programming language, we calculated the three-dimensional space velocity components and their uncertainties for individual stars in the Gaia catalog. Once these values were determined, we developed a method to search through the catalog and identify stars with common kinematic properties that have potential to constitute a moving group. We have compiled a list of 450 candidate moving groups with at least five members; 38 of the candidate groups contain ten or more members. These data will be used in future observing projects to look for other indications, such as common metallicities, to confirm the possible members are related.

1 INTRODUCTION

Gaia

The European satellite mission Gaia was launched in December 2013, and over the course of the past five years it has take unprecedented positional measurements for one percent of the Galaxy's one hundred billion stars. The ultimate goal is to create the world's largest three-dimensional map of the Milky Way. Gaia is accurately measuring the motion of each star it detects. The motion of a star is decided at star birth, unless it is altered by interactions with other massive objects. Studying these stellar motions allows us to see how the Galaxy first formed. The first set of data was released in December 2017 based on observations collected between July 2014 and September 2015. It included five-parameter astrometric data—positions, parallaxes, and proper motions—for about two million stars in common with Hipparcos and the Tycho-2 catalogue (Gaia Collaboration et al., 2016). The Tycho-2 catalogue is an astrometric and photometric reference catalog from 2000 based on observations from the European satellite Hipparcos.

Open Clusters

Like all star formation, open clusters begin as one giant cloud of gas and dust that develops into dozens or thousands of dense clumps that contract to form individual stars. When individual stars bind together by their mutual gravity they form an open cluster, and the stars orbit the cluster's center of mass along different orbital paths. Open clusters are characterized as being loosely bound, asymmetrical, and metal rich (metallicities similar to the Sun). They consist of relatively young stars so we expect to find them in the Milky Way plane, which makes them hard to observe as they are hidden behind dust and the high density star field. Only a small fraction of open clusters have been cataloged, mainly nearby ones, such as the Pleiades and Hyades (Binney & Merrifield, 1998).

Moving Groups

The first identified moving group was an unintentional discovery made by German astronomer J.H. von Mädler in the 18th century. Mädler was trying to determine the motion of the Sun by measuring the proper motions of nearby stars. While doing so, he noticed that eleven of the stars in the open cluster Pleiades had the same proper motion as a large fraction of stars located several degrees away from the group. This led to the discovery of the Pleiades moving group (Antoja et al., 2010).

Today we know that because open clusters are located in the Galactic plane, they are often disrupted by tidal encounters. Tidal forces cause individual members of the weakly bound open cluster to be pulled away (Binney & Merrifield, 1998). It has been discovered that former members continue to move in the direction that the cluster was moving at the time it was disrupted. These individual stars will continue to follow similar orbits in the Galaxy even though they are no longer gravitationally bound together. Another form of disruption to an open cluster occurs during the equipartion process, which is when low mass stars within a cluster gain enough energy to reach velocities higher than the systems' escape velocity. When members escape from a cluster via this process it is called evaporation (Binney & Merrifield, 1998).

Disrupted members from a given open cluster are collectively known as a moving group. Members will have similar velocities and metallicities even though they are now spread out across the sky. Many of the stars in the disk of the Milky Way are from disrupted open clusters Binney & Merrifield (1998).

2 METHODS

To determine if stars in the Milky Way comprise a moving group we must look at their kinematic properties. Gaia's first data release (DR1) contains the parallax, proper motions, and uncertainties for nearly two million stars. We needed to calculate the Galactic space-velocity components: U,V, and W, for these stars. U is the radial velocity component that is positive toward the Galactic Center, V is the azimuthal component that is positive in the direction of the Galactic rotation, and W is perpendicular to the plane and positive toward the North Galactic Pole (Antoja et al., 2010).

Johnson & Soderblom (1987) present formulas for computing a star's Galactic space velocity components from its proper motion, parallax, and radial velocity, along with formulas for uncertainties in the components (σ_U, σ_V, and σ_W) based on uncertainties in the observed quantities. Gaia's first data release does not include the radial velocity measurements, which are required to find U, V, and

W for these stars. Gaia's full astrometric, photometric, and radial-velocity catalogues will not be available until the final release at the end of 2022.

The fifth data release (DR5) from the Radial Velocity Experiment (RAVE) contains radial velocities and uncertainties for randomly selected stars in the southern hemisphere (Kunder et al., 2017). Using the Python programming language, and the pandas package, we combined the RAVE DR5 and Gaia DR1 catalogs based on the stars' Tycho identification. The code we developed read in the Gaia data file and created a new data frame consisting only of the pertinent data—in this case the Tycho identification, right ascension, declination, proper motion in right ascension and declination, parallax, and uncertainties. Then the code read in the RAVE data file, and created another data frame extracting only the relevant data—Tycho identification, radial velocity, and uncertainty. Finally, we merged the data frames based on common Tycho identification's to create our sample to search for possible moving groups.

With the radial velocities included in our sample, Johnson & Soderblom's formulas can be utilized. The formulas use a right-handed coordinate system, meaning U, V, and W are positive in the direction of the Galactic center, Galactic rotation, and the North Galactic Pole (NGP), respectively, as described earlier. This system allows for us to use the same matrix for transforming both coordinates and velocities (Johnson & Soderblom, 1987). To begin, the Galactic coordinates must be defined by three angles, where α and δ are equatorial coordinates of the North Galactic Pole and θ is the position of the North Celestial Pole: (α_{NGP}, δ_{NGP}, θ_0) = (193.0421°, 27.0469°, 123°).

θ_0 is relative to the great semicircle passing through the NGP and zero Galactic longitude (Johnson & Soderblom, 1987). The formula also requires the following observed quantities and their uncertainties: $\pi \pm \sigma_\pi$, parallax in arcsec; $\rho \pm \sigma_\rho$, radial velocity in $\mathrm{km\,s^{-1}}$; $\mu_\alpha \pm \sigma_{\mu_\alpha}$, proper motion in right ascension in $\mathrm{arcsec\,yr^{-1}}$; $\mu_\delta \pm \sigma_{\mu_\delta}$, proper motion in declination in $\mathrm{arcsec\,yr^{-1}}$.

Transforming Coordinates and Calculating Space Velocities

Using matrix multiplication we can transform equatorial coordinates to Galactic coordinates (Johnson & Soderblom, 1987):

$$\begin{bmatrix} c\cos b\,\cos l \\ \cos b\,\cos l \\ \sin b \end{bmatrix} = \mathbf{T} \begin{bmatrix} c\cos\delta\,\cos\alpha \\ \cos\delta\,\cos\alpha \\ \sin\delta \end{bmatrix}$$

where $\mathbf{T}$ is the transformation matrix:

$$\mathbf{T} = \begin{bmatrix} +\cos\theta_0 & +\sin\theta_0 & 0 \\ +\sin\theta_0 & -\cos\theta_0 & 0 \\ 0 & 0 & +1 \end{bmatrix} \begin{bmatrix} -\sin\delta_{NGP} & 0 & +\cos\delta_{NGP} \\ 0 & -1 & 0 \\ +\cos\delta_{NGP} & 0 & +\sin\delta_{NGP} \end{bmatrix} \times \begin{bmatrix} +\cos\alpha_{NGP} & +\sin\alpha_{NGP} & 0 \\ +\sin\alpha_{NGP} & -\cos\alpha_{NGP} & 0 \\ 0 & 0 & +1 \end{bmatrix}$$

Next, we define the coordinate matrix:

$$\mathbf{A} \equiv \begin{bmatrix} +\cos\alpha\cos\delta & -\sin\alpha & -\cos\alpha\sin\delta \\ +\sin\alpha\cos\delta & +\cos\alpha & -\sin\alpha\sin\delta \\ +\sin\delta & 0 & +\cos\delta \end{bmatrix} = \begin{bmatrix} \cos\alpha & \sin\alpha & 0 \\ \sin\alpha & -\cos\alpha & 0 \\ 0 & 0 & -1 \end{bmatrix} \begin{bmatrix} \cos\delta & 0 & -\sin\delta \\ 0 & -1 & 0 \\ -\sin\delta & 0 & -\cos\delta \end{bmatrix}$$

From here we can calculate the Galactic space-velocity components:

$$\begin{bmatrix} U \\ V \\ W \end{bmatrix} = \mathbf{B} \begin{bmatrix} \rho \\ k\mu_\alpha/\pi \\ k\mu_\delta/\pi \end{bmatrix} \tag{1}$$

where $\mathbf{B} = \mathbf{T}\cdot\mathbf{A}$ and $k = 4.74057\,\mathrm{km\,s^{-1}}$, the equivalent of one astronomical unit in one tropical year (Johnson & Soderblom, 1987).

Calculating Uncertainties in Velocity Components

The standard formula for calculating the variance of a multi-variable function is:

$$\sigma^2_{F(x,y,z)} = \left(\frac{\partial F}{\partial x}\right)^2 \sigma_x^2 + \left(\frac{\partial F}{\partial y}\right)^2 \sigma_y^2 + \left(\frac{\partial F}{\partial z}\right)^2 \sigma_z^2$$

This formula is valid for us to use, because none of our uncertainties are correlated. Assuming $\mathbf{T}$ and $\mathbf{A}$ do not cause uncertainty on U, V, and W, we can apply this formula to Equation 1 and calculate the uncertainties of the velocity components:

$$\begin{bmatrix} \sigma_U^2 \\ \sigma_V^2 \\ \sigma_W^2 \end{bmatrix} = \mathbf{C} \begin{bmatrix} \sigma_\rho^2 \\ (k/\pi)^2[\sigma^2_{\mu\alpha} + (\mu_\alpha\sigma_\pi/\pi)^2] \\ (k/\pi)^2[\sigma^2_{\mu\delta} + (\mu_\delta\sigma_\pi/\pi)^2] \end{bmatrix} + 2\mu_\alpha\mu_\delta k^2\sigma_\pi^2/\pi^4 \begin{bmatrix} b_{12}\cdot b_{13} \\ b_{22}\cdot b_{23} \\ b_{32}\cdot b_{33} \end{bmatrix} \tag{2}$$

where matrix $\mathbf{C}$ contains the squares of the individual elements of matrix $\mathbf{B}$, $c_{ij} = b_{ij}^2$ for all i and j (Johnson & Soderblom, 1987). Coding the transformation matrices and Equations 1 and 2 into Python allows us to efficiently calculate the Galactic space velocity components and their uncertainties for every star in the data set.

Determining Potential Moving Groups

Members of a moving group have similar kinematic properties so their Galactic space velocity components will be similar. Grouping stars from our data based on shared U,V, and W components will compile a list of potential moving groups. Using the pandas package in Python, we can create a function that takes in a parameter U_i and uncertainty σ_{U_i} for an individual star i. It will then compare the value of U_i to the values of U for all of the other stars in the data frame, and output a group of stars whose U component is within the given uncertainty, σ_{U_i}. The function will repeat this process on star i for two more parameters (V_i and W_i) and uncertainties (σ_{V_i} and σ_{W_i}). Stars that do not match all three parameters will be eliminated from the group.

We complied a pandas dataframe for each individual star in our data set. As it checks each individual star against the entire data set

	Tycho2 ID	U (km s^{-1})	V (km s^{-1})	W (km s^{-1})	σ_U	σ_V	σ_W
1	5261-528-1	-57.687	-40.808	-35.815	4.269	3.580	1.404
2	5592-412-1	-51.884	-41.596	-36.248	1.184	2.0182	0.984
3	6436-287-1	-53.729	-42.832	-34.887	4.736	3.708	2.556
4	6534-247-1	-58.201	-42.489	-33.403	0.776	0.955	0.641
5	6648-156-1	-51.595	-46.091	-34.648	3.142	1.792	2.585
6	7013-529-1	-55.714	-43.826	-33.801	4.274	2.667	2.213
7	7567-840-1	-53.041	-44.909	-35.110	4.277	1.754	1.743
8	7751-1047-1	-49.430	-42.203	-32.631	3.013	1.857	2.045
9	8314-458-1	-54.370	-41.315	-33.411	1.759	3.670	2.126
10	8441-432-1	-57.776	-44.516	-35.157	4.863	3.955	3.292
11	8490-1014-1	-52.443	-45.624	-32.658	4.983	1.818	1.028
12	8514-1319-1	-50.686	-44.001	-37.083	4.207	1.308	2.000
13	8864-614-1	-56.518	-45.879	-37.243	4.693	1.787	1.542
14	9328-51-1	-57.400	-41.229	-34.844	3.783	2.428	1.950
15	9432-1514-1	-58.054	-45.000	-33.403	4.792	3.065	2.570

Table 1. The calculated U, V, W space velocities and uncertainties for 15 potential members of a moving group.

	Tycho2 ID	ra (degrees)	dec (degrees)	μ_α (arcsec yr^{-1})	μ_δ (arcsec yr^{-1})	π (arcsec)	ρ (km s^{-1})
1	5261-528-1	3.674	-9.349	103.438 $\pm$ 1.583	-21.469 $\pm$ 0.928	6.569 $\pm$ 0.476	21.524 $\pm$ 0.843
2	5592-412-1	226.048	-13.609	-58.190 $\pm$ 1.845	-52.993 $\pm$ 0.793	6.976 $\pm$ 0.238	-53.622 $\pm$ 1.116
3	6436-287-1	37.865	-27.975	28.954 $\pm$0.785	3.546 $\pm$ 0.708	2.729 $\pm$ 0.333	58.058 $\pm$ 1.036
4	6534-247-1	102.961	-29.138	-70.861 $\pm$ 1.307	47.630 $\pm$ 1.117	12.057 $\pm$ 0.241	71.984 $\pm$ 1.009
5	6648-156-1	165.361	-29.729	-103.141 $\pm$ 0.910	-24.895 $\pm$ 0.477	6.730 $\pm$ 0.389	20.017 $\pm$ 0.773
6	7013-529-1	37.977	-34.834	28.595 $\pm$ 0.518	7.498 $\pm$ 0.923	2.579 $\pm$ 0.237	56.707 $\pm$ 1.507
7	7567-840-1	47.208	-44.605	23.076 $\pm$ 0.744	14.439 $\pm$ 0.769	2.622 $\pm$ 0.238	60.335 $\pm$ 0.790
8	7751-1047-1	172.116	-44.902	-95.202 $\pm$ 0.963	-22.331 $\pm$ 0.350	6.522 $\pm$ 0.354	15.425 $\pm$ 1.122
9	8314-458-1	240.387	-47.176	-25.511 $\pm$ 1.025	-62.697 $\pm$ 0.411	4.661 $\pm$ 0.300	-32.261 $\pm$ 0.496
10	8441-432-1	330.574	-48.182	68.526 $\pm$ 0.400	-32.849 $\pm$ 0.801	4.452 $\pm$ 0.383	-2.831 $\pm$ 0.808
11	8490-1014-1	37.473	-59.821	31.055 $\pm$ 0.365	19.074 $\pm$ 0.868	2.806 $\pm$ 0.233	45.911 $\pm$ 0.801
12	8514-1319-1	79.514	-56.330	0.0751 $\pm$ 0.619	26.746 $\pm$ 0.983	2.74 $\pm$ 0.229	61.088 $\pm$ 1.268
13	8864-614-1	38.008	-66.084	49.166 $\pm$ 0.483	39.698 $\pm$ 0.811	4.389 $\pm$ 0.308	45.037 $\pm$ 1.920
14	9328-51-1	331.642	-69.505	70.523 $\pm$ 0.656	-28.767 $\pm$ 1.066	4.613 $\pm$ 0.271	9.016 $\pm$ 1.059
15	9432-1514-1	221.118	-77.239	-44.656 $\pm$ 0.393	-52.807 $\pm$ 0.918	4.079 $\pm$ 0.309	7.267 $\pm$ 0.734

Table 2. The observed right ascension, declination, proper motions, parallax, and radial velocity for 15 potential members of a moving group.

it will output each star's group as a new data frame and compile these data frames (which are potential groups) into a list. We set the function to disregard all potential groups containing less than five candidate members.

3 RESULTS AND DISCUSSION

We used the data in the RAVE DR5 catalog to find the radial velocity and uncertainty for 247,403 stars in the Gaia DR1 catalog. There were multiple measurements of radial velocity (RV) for a significant portion of the stars in the RAVE catalog. Repeated RV measurements were used to characterize the uncertainty in the RVs, so there are 43,918 duplicate stars that were observed more than once (Kunder et al., 2017). Eliminating these duplicates, based on the lowest RV error, reduced our number of stars to 208,589.

We calculated the average error and standard deviation for each observed quantity, and removed all stars with errors greater than the average plus one standard deviation. This further reduced our data set down by about 100,000 stars. From here, the Galactic space velocity code was run across the data set. A large fraction of stars had extremely high uncertainties in their space velocity components. Deleting stars with uncertainties greater than the average plus one standard deviation would not work for these calculated quantities as the standard deviation is too large. Instead, we removed all stars with errors (σ_U, σ_V, and σ_W) higher than 10% of their U, V, and W velocity components, respectively. Our final data set contains 9,339 stars.

Using the function described earlier, that compares elements based on three parameters (U, V, and W), our code compiled a data set of 449 candidate moving groups that contain at least five potential members. Thirty eight of the candidate moving groups contain ten or more members. The two largest groups consist of 16 members. Our calculated space velocities for members of one of the potential moving groups along with the observed stellar data

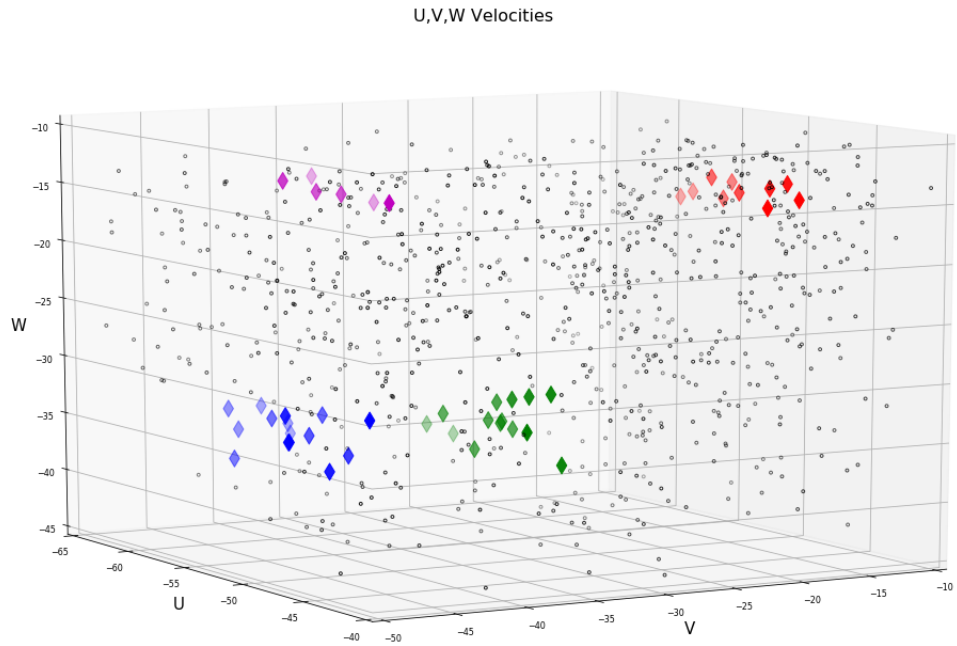

Fig. 1. The final data set of stars plotted by their calculated U, V, W space velocity components. We extracted a small portion of the graph and highlighted four potential moving groups, marking members of each group by respective colors.

from Gaia and RAVE are given in Table1 and Table 2. Four of the candidate moving groups are plotted in velocity space in Figure 1. The set of stars from Table1 is shown in blue.

Stars from a respective group are located close to each other in three dimensional velocity space since they have similar kinematic properties. This figure can be misleading as it makes the potential moving group members look close together in space. Plotting the locations of stars in these candidate moving groups allows us to see how spread out the potential members actually are. Using the measured right ascension and declination from the Gaia catalog, we plotted the stars by their Galactic coordinates in Figure 2. As expected, stars from a given moving group are spread out across the Galaxy. The U-shaped gap in the center is from the plane of the Galaxy cutting through the spherical night sky.

These potential moving groups all contain stars from the southern hemisphere as we only had the required information to calculate the Galactic space velocities for stars that were also in the RAVE catalog. The RAVE experiment was restricted to measuring radial velocities of stars in the southern hemisphere. Until Gaia releases its radial velocity measurements, our sample is limited.

4 SUMMARY

Gaia's first data release provided us with the necessary stellar kinematic information needed to begin the process of identifying moving groups of stars in the Galaxy. Although the radial velocities from the Gaia satellite were not provided in this initial data set, we were able to take radial velocities from the RAVE catalog, an earlier experiment that measured radial velocities for stars in the southern hemisphere. After cross matching Gaia and RAVE stars by their Tycho2 ID, we obtained enough information to calculate the Galactic space velocities for 208,589 stars in the southern hemisphere. Using the transformation matrices and space velocity equations presented by Johnson and Soderblom (1987), we developed a Python code to calculate U ,V, and W velocities for each star from their observed proper motion in right ascension and declination, parallax, and radial velocity. We removed all stars from the data set that had relatively high uncertainties in their observed and calculated kinematic properties, resulting in a final data set of 9,339 stars. Finally, our code identified and grouped together stars with common motions. We found 449 potential moving groups that contain at least five stars, and 38 of which contain 10 or more members. Plotting the moving group members in both velocity space and Galactic coordinates confirmed that members share common motions but are spread out across the Galaxy. Until the Gaia working group releases radial velocity measurements for all of its observed stars, our results will be limited to moving groups with members in the southern hemisphere. Further observations and studies of the discovered members' metallicities must be completed to verify that they constitute moving groups.

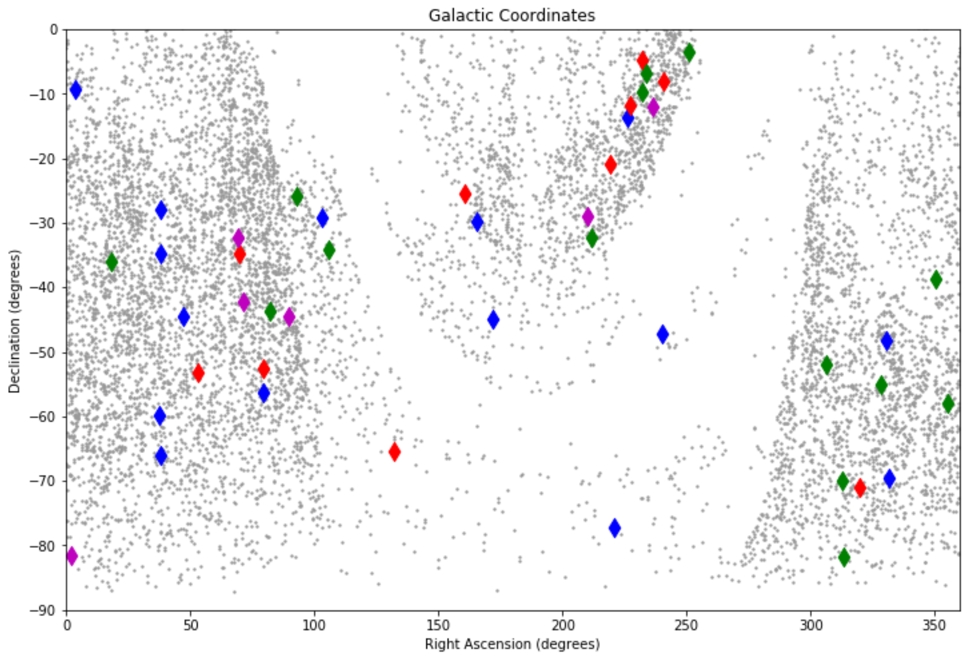

Fig. 2. The final data set of stars plotted by their right ascension and declination in degrees. Concentrating on an area of the southern hemisphere, we highlighted stars from the four potential moving groups that were shown in U, V, W space.

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REFERENCES

Antoja, T., Figueras, F., Torra, J., et al. 2010, Lecture Notes and Essays in Astrophysics, 13

Binney, J., & Merrifield, M. 1998, Galactic astronomy / James Binney and Michael Merrifield. Princeton

Gaia Collaboration, Brown, A. G. A., Vallenari, A., et al. 2016, Astron Astrophys, 595, A2

Johnson, D. R. H., & Soderblom, D. R. 1987, Astron J, 93, 864

Kunder, A., Kordopatis, G., Steinmetz, M., et al. 2017, Astron J, 153, 75