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# Theia 456 and Its Stellar Components

Trevor Kattenberg and Simon Schuler[1]

Department of Physics, University of Tampa, Tampa, FL 33606, [1]Faculty Advisor

## ABSTRACT

The release of Gaia astrometric data has allowed for machine learning to locate hundreds of potentially new Galactic star clusters and moving groups. Our research is focused on one such association of stars, Theia 456. Theia 456 is a stellar filament of an estimated 468 stars that is within 1 kpc of the Sun, and our group's preliminary analysis suggests stars in Theia 456 share similar compositions. Due to these properties, Theia 456 is considered primordial, resulting from the Galactic stellar formation process rather than the result of dynamical processes such as tidal stripping. Our research is focused on utilizing a python code we have developed to analyze positions, proper motions, and parallaxes of stars in the second data release (DR2) of the Gaia catalog to confirm or reject the stellar members of Theia 456. We endeavor to verify the validity of Theia 456 as a primordial stellar filament and possibly identify additional members of the association. This research will contribute to our understanding of the evolution of the Milky Way Galaxy.

## 1 INTRODUCTION

### Open Cluster

Opens clusters are areas of stellar formation and typically occur in spiral and irregular galaxies. These stellar conglomerates are small, typically 2,000 stars or less, and consist of stars that have formed from a collapsed dust cloud. Due to the stars being formed from the same dust cloud, they share characteristics such as similar chemical compositions, age, and velocities. However, due to its relatively small size, these clusters are dispersed within a few hundred million years.

The dissociation of open clusters occurs due to tidal stripping. Tidal stripping describes the process by which a massive object can influence the motions of stars in the cluster through its gravitational pull. These tidal forces are caused by a massive object or a large dust cloud passing near the cluster. Specifically, tidal stripping results in tidal gravitational forces being exerted on the objects in the cluster causing the cluster to elongate. Eventually, the stars become unbound to the cluster due to the decreasing gravitational potential energy of the cluster. This is what we believe occurred to a previous open cluster named Theia 456.

### Theia 456

Theia 456 is a stellar stream identified by Kounkel & Covey (2019) through their use of an unsupervised machine learning program called HBDSCAN. The stream is estimated to be 170 million years old and contains 486 stars that span 20 degrees and 175 parsecs. We believe that this association is in the process of being tidally stripped due to our group's previous work that determined the position of the stream was more tightly bound 60 million years ago (Andrews et al., 2021). Further analysis by our group determined that 87 stars have similar compositions based on the LAMOST spectroscopic catalog (Yao et al., 2019), which provided more evidence that this association was an open cluster.

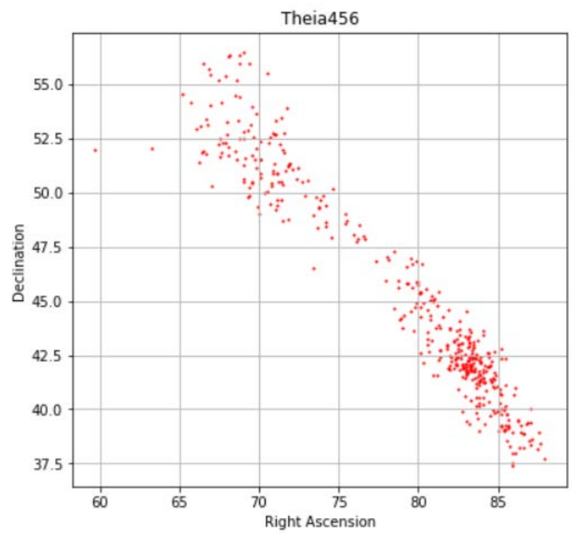


**Fig. 1.** Figure 1: Degree Spread of Theia 456

### GAIA

GAIA is a satellite of the European Space Agency whose mission is to obtain information on stellar objects in the Milky Way Galaxy. The mission will measure properties such as proper motion and luminosity from an estimated 1.3 billion stars in the Milky Way Galaxy. The data collected from the satellite are released in batches with three different data sets already released, DR1 (2016), DR2 (2018) and DR3 (2020). Note that our research focused on the DR2 data set.

## 2 METHODS

We utilized a modified version of a python code developed by Dr. Andrews of Northwestern University (Andrews et al., 2017) to analyze Theia 456 (see Jennings et al. in this volume for details). To use the code, we separated the GAIA DR2 data into regions dependent upon their galactic positions. Once the stars were separated, the code used a posterior probability ($P_{\mathrm{post}}$) to determine the statistical relationship between two stars. The probability was calculated from the proper motion, parallax, and position of the stars where the parallax and position, i.e. right ascension and declination, are set by the user. Two stars with a similar position, proper motion,

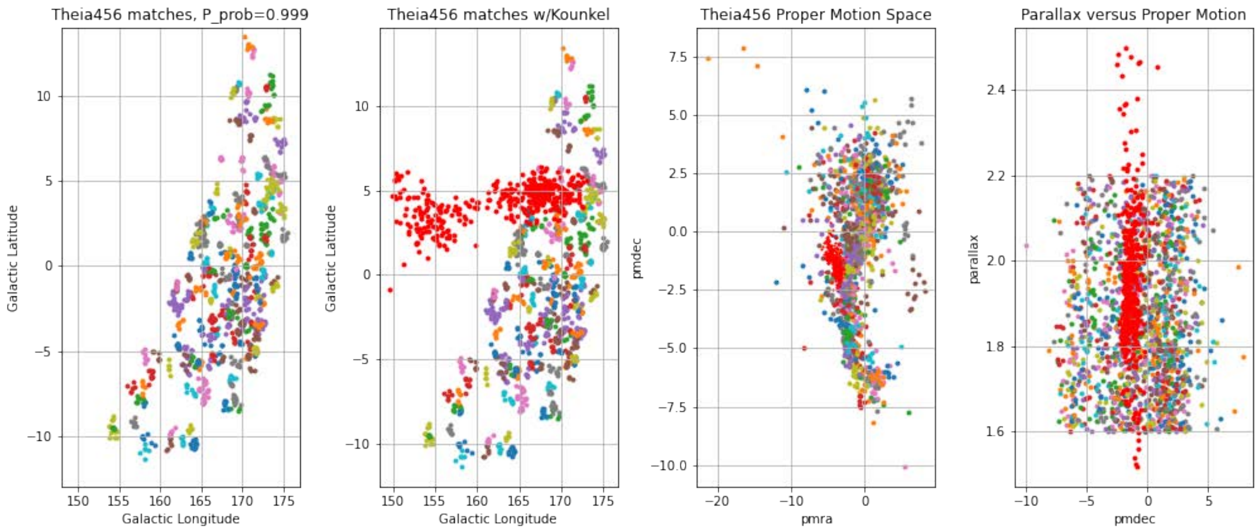


**Fig. 2.** Figure 2:Theia 456 full sky run, $P_{\text{post}} = 0.999$. A full sky run refers to a right ascension of 75°, declination of 48°, and a search radius of 15°

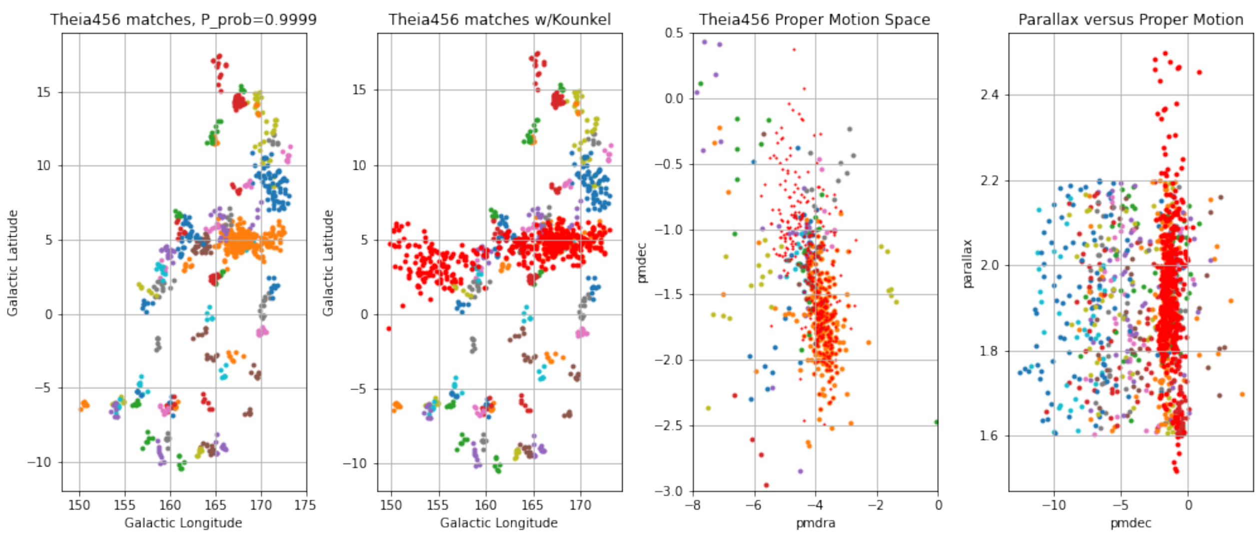


**Fig. 3.** Figure 3:Theia 456 full sky run, $P_{\text{post}} = 0.9999$. A full sky run refers to a right ascension of 75°, declination of 48°, and a search radius of 15°

and parallax have a higher likelihood to be matched than stars with similar proper motions but differing parallaxes. In our experiment, we used a parallax range of 1.6 to 2.2 arcseconds, and a right ascension and declination of 75° and 48°, matching the estimated distance and position of Theia 456.

After the code collected these binary pairs, $P_{\text{post}}$ was used to calculate the likely hood that a set of binary stars were related to another. If the binary pairs exceeded a threshold probability determined by the user, then the set of binary stars were determined to be a cluster. In our experiment, we used two different threshold probabilities, $P_{\text{post}} = 0.999$ and $P_{\text{post}} = 0.9999$.

## 3 RESULTS

The results for our four runs are shown in Figures 2, 3, 4 and 5. The four runs differ in terms of position and $P_{\text{post}}$. In terms of Galactic position, Figure 2 and Figure 3 are focused on a full sky run while Figures 4 and 5 are focused on the Western portion of Theia 456, i.e Galactic Longitude (150°,160°) and Galactic Latitude (0°,7°). For $P_{\text{post}}$, Figure 2 and Figure 4 shows runs subject to a $P_{\text{post}}$ of 0.999, and Figure 3 and Figure 5 shows runs for a $P_{\text{post}}$ of 0.9999.

Each figure contains four sub graphs. The first two sub graphs detail the Galactic position of the stars with sub graph 2 displaying our results as well as (Kounkel & Covey, 2019) in red. The last

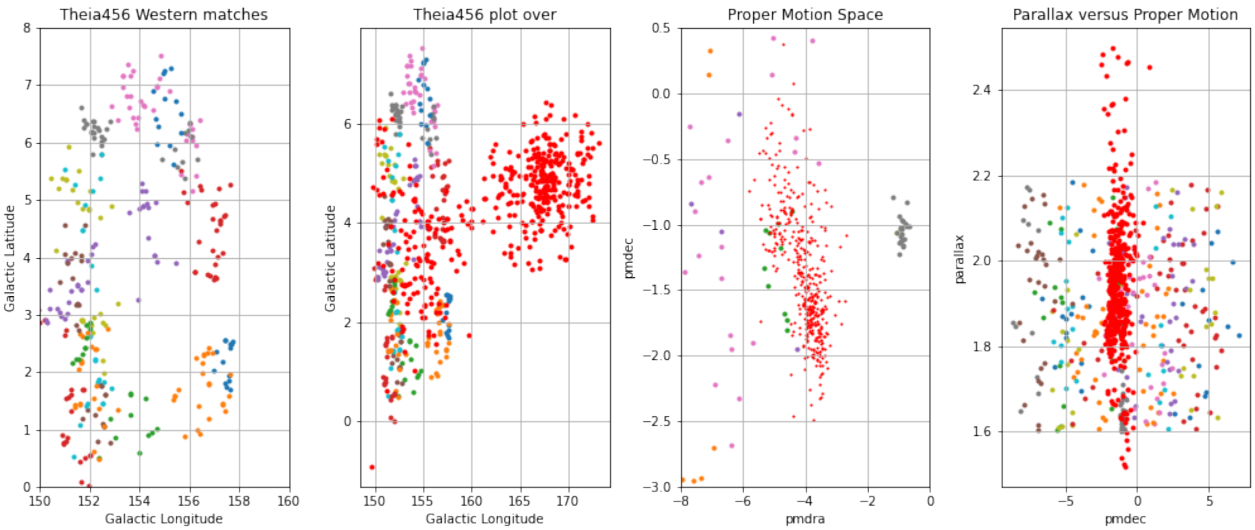


**Fig. 4.** Figure 4: Theia 456 western run, $P_{\text{post}} = 0.999$. A western run refers to a run focused on the Galactic longitudes less than 160.

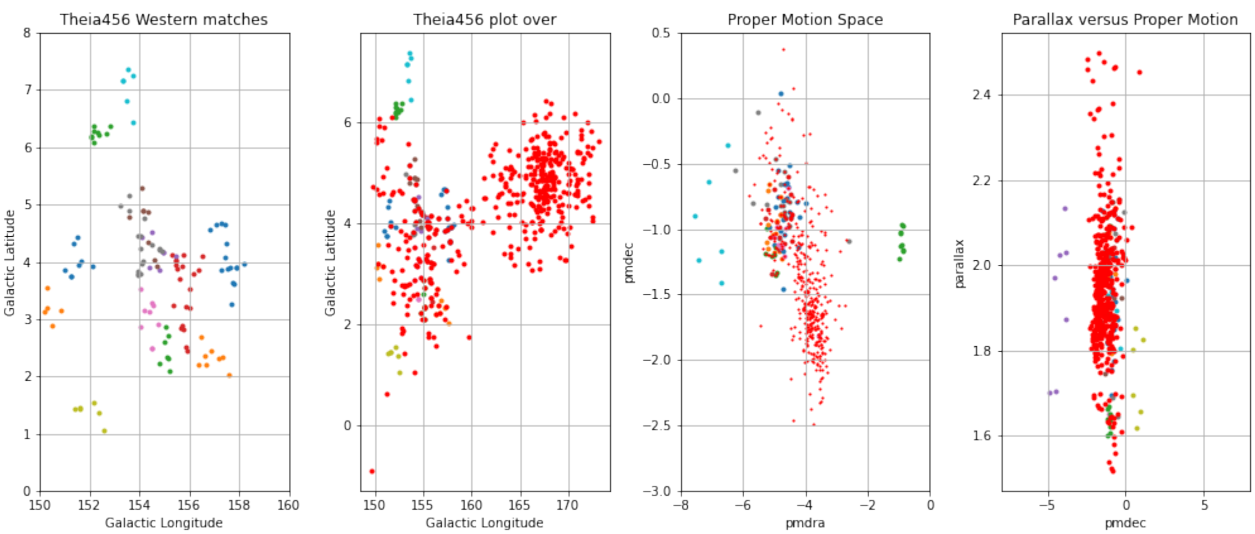


**Fig. 5.** Figure 5: Theia 456 western run, $P_{\text{post}} = 0.9999$. A Western Run refers to a run focused on the Galactic longitudes less than 160.

two sub graphs show the proper motion and parallax of the matched pairs. Similar to (Kounkel & Covey, 2019, sub graph 2) results are plotted in red.

## 4 DISCUSSION/CONCLUSION

We use the GAIA DR2 catalog to obtain our results from the python code, and Figures 2, 3, 4 and 5 display the outputs of these various runs. As mentioned above, the exogenous variables in the algorithm are the right ascension, declination, search radius, and the $P_{\text{post}}$. For the first two figures, a right ascension of 75°, declination of 48°, and a search radius of 15° were chosen to try and replicate the results of Kounkel & Covey (2019). For Figures 4 and 5, a right ascension of 68°, a declination of 51.2°, and a search radius of 2° were selected to analyze the Western portion of the association, Galactic Longitude (150°, 160°) and Galactic Latitude (0°, 7°).

Figure 2 shows the results for the cluster subject to a $P_{\text{post}}$ of 0.999 where the $P_{\text{post}}$ refers to a likelihood that the matched pairs are a stellar association. Our calculated Theia 456 clusters are shown by a variety of colors, where each color indicates a potential Theia 456 match. Since our groups previous analysis has determined that Theia 456 is most likely a disassociated stellar cluster, our matches should have similar proper motions and galactic positions. Note, the position of our cluster is displayed in the first two panels in each Figure, while proper motion is shown in the third and fourth panels.

The bulk of the matches in Figure 2 cluster around a galactic longitude of 160° to 175° and a galactic latitude of −5° to 5°. To determine the accuracy of our model, we plotted (in red) the previously determined position of Theia 456 as determined by Kounkel & Covey (2019) over our results in the second panel of Figure 2. As can be seen, our results have a larger spread that of Kounkel and Covey, and our matches do not map well with the Western portion of Theia 456, stars to the left of galactic coordinate (160°, 4°). Besides having a wider positional spread, an analysis of third panel of Figure 2 shows that the proper motion of our matches do not correlate with the results of the previous studies; the range of proper motion is much wider in our results. Thus, based on the position and proper motion of the matched clusters, we believe background stars are being matched as Theia 456, so we determined that the exogenous variable, $P_{\mathrm{post}}$ needed to be increased.

We increased the $P_{\mathrm{post}}$ to 0.9999, while the other, exogenous variables were kept constant with respect to Trial 1; the results are shown in Figure 3. Because we increased the requirements needed for pairs of stars to be considered a cluster, we expected the number of matches to decrease from Trial 1 to Trial 2 which is evident from the first panels of each figure. However, more associations were found at galactic coordinates (165°, 5°) than in Trial 1. Second, as can be seen in panel 2 of Figure 3, more of our matches overlap with Kounkel and Covey data. Specifically, the orange cluster is closely associated with previous coordinates of Theia 456. Finally, the proper motion of the orange cluster is comparable to the proper motion of Theia 456 determined by Kounkel and Covey (panel 3 of Figure 3). Even though, the accuracy of our matches increased with respect to the previous literature, the Western portion of Theia 456 lacked accurate matches. Thus, we determined that a run—focusing on the density of stars to left of Galactic coordinates (160°, 5°)—as required to investigate why the code was not matching stars in the Western portion of the stellar stream.

Figure 4 and Figure 5 display the output for runs focused on the more dispersed region of the Western section of Theia 456. Figure 4 shows the output for a $P_{\mathrm{post}}$ of 0.999 while Figure 5 shows the run subject to the same parameters but with a $P_{\mathrm{post}}$ of 0.9999.

The first panel of Figure 5 shows a small number of associations to the left of galactic longitude 160°. However, when these results are plotted over those of Kounkel and Covey in the second panel of Figure 5, our matches fail to identify most of Theia 456. However, some of our associations, such as the orange and blue clusters, do overlap with Theia 456 with the proper motion of these clusters matching the proper motion of Theia 456, indicating these clusters could indeed be Theia 456. However, most of the Western association is still not being identified by our code when subject to a $P_{\mathrm{post}}$ of 0.9999. Thus, we believe that too many stars were being excluded from the result, so we ran the code subject to a $P_{\mathrm{post}}$ of 0.999 with the output graphed in Figure 4. This run matched more associations to Theia 456. However, the greater number of matches were not confirmed when compared to the position of Theia 456 (second panel of Figure 4), the proper motion of Theia 456 (third panel), and the parallax of Theia 456 (fourth panel).

## 5 SUMMARY

In our research, we have identified a section of Theia 456. This section is clustered around the Galactic coordinates (165°, 5°) and was identified based upon their position, proper motion, and parallax relative to the Kounkel and Covey (2019) results. The stars in this portion of Theia 456 are more tightly bound and their proper motions have less variance than the Western portion of stars, stars with a Galactic longitude less than 160°.

Future research by this group will focus on determining why the code is unable to match the less dense regions of the Theia 456. Secondly, research will also focus analyzing the GAIA DR2 and DR3 catalogs to identify more stellar streams, because we believe stellar streams will allow researchers a better understanding of how the Milky Way Galaxy evolved.

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