Acta Spartae Vol. 5 No. 1 2021
Pages 6–10

Searching for Stellar Associations in Gaia DR2

Brolan Jennings[1], Simon Schuler[1,5], Jeff Andrews[2], Marcel Agüeros[3], and Julio Chanamé[4]

[1]University of Tampa, Tampa, FL, [2]CIERA/Northwestern University, Chicago, IL, [3]Columbia University, New York, NY, [4]Pontificia Universidad Católica de Chile, Santiago, Chile, [5]Faculty Advisor

ABSTRACT

We present preliminary results of a search for previously unidentified stellar associations in the second data release (DR2) from the European Space Agency's Gaia satellite. Gaia DR2 contains precise astrometric data on more than 1.2 billion stars in the Milky Way Galaxy. We have modified a Python code originally intended to identify wide stellar binaries through a Bayesian formulation, which includes correlated uncertainties in the proper motions and parallaxes, to expand it to larger stellar groups of 10 or more stars. The search volume includes the whole sky within 500 parsecs of the sun, where stellar parallaxes are more discernible. The code has been optimized to filter out background stars by testing over several well known stellar associations, including the Pleiades open cluster and the Scorpius-Centaurus Association. We have been able to successfully identify the Pleiades, Upper Scorpius Centaurus, and Messier 39 stellar associations with our code and are now searching the sky for previously unidentified associations. Identifying new stellar associations will help constrain models of the dynamical evolution of the Galaxy.

Fig. 1. The Pleiades open cluster has been known to civilizations across the world for thousands of years, with the first depiction of the cluster being on a bronze age disk dated to approximately 1600 BCE (Ehser et al., 2011).

1 INTRODUCTION

When looking up at the night sky, even with the naked eye, one can identify many distinct features of our solar neighborhood. In addition to the other planets of our solar system, constellations, and the milky band of our galaxy, one might also note distinct regions of overdensities of stars, which we call open clusters. The most notable open cluster is the Pleiades, shown in Figure 1, which is visible from the north pole to South America. The Pleiades has been observed for thousands of years, as it is a collection of extremely bright, blue stars tightly bound on a small section of the sky.

The Pleiades (as well as other open clusters) became even more interesting with the advent of the telescope, which allowed precise measurements of stellar proper motion. Proper motion is how we measure a star's motion in the sky, relative to background stars, as we see it from the Earth. Figure 2 shows the proper motion of Barnard's star, the star with the highest proper motion, over a 16 year period. We measure proper motion in right ascension (pmra) and in declination space (pmdec,) analogous to longitude and latitude on Earth. By taking precise proper motions of stars, astronomers were able to show that, in general, different stars move at different rates and in different directions. This was not the case for the stars of the Pleiades, all of which moved in the same direction and at the same rate. These new observations were beginning to prove what astronomers had assumed for some time – that these clusters of stars were deeply related.

As telescopes became more advanced and achieved higher light gathering capabilities, astronomers were able to record increasingly accurate catalogs of stars and their motions across the night sky. These improvements have continued until today, with new catalogs from space-based telescopes collecting data on billions of stars, all with a higher precision than even Galileo could have imagined. As our catalogs of stars and star clusters have grown dramatically, so too has our understanding of them and their evolution. The more we understand the stars, the more out overall understanding of the evolution of the universe grows. We have learned of the nuclear processes that take place in stellar interiors and how generations of stars are responsible for the fusing of hydrogen and helium into every other naturally occurring element in the Universe (with the exception of Lithium, Beryllium, and Boron, which are created through interactions with cosmic rays from sources such as black holes.) We have learned more about the ways in which planets form in accretion disks of gas and dust around stars and how for the billions of stars in our galaxy there at least as many billions of planets. We have learned something, too, of the way stars form together in clusters and slowly drift apart.

For each answer and new discovery we make about our Universe, however, we stumble upon even more questions. For instance, if stars form in the same region (like with the Pleiades) why do most of them appear so isolated on the night sky? Did they form there independently, or were they once part of their own star cluster? If they were once part of a cluster, is it possible to identify the other former members of that cluster? Would these stars be the same age? Would they have the same relative elemental composition? Could the answers to these questions yield insight into the conditions necessary for a star to form planets? If so, would we be able to tell what conditions would be necessary to form rocky, Earth-like planets, as opposed to giant, Jupiter-like planets? These questions

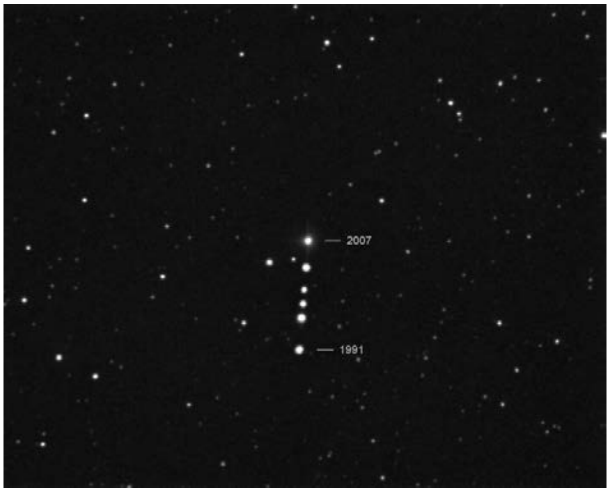

Fig. 2. Named after the American astronomer E.E. Barnard, Barnard's star has the highest proper motion for any known star with respect to the sun of 10.3 arcseconds per year. Above is Barnard's star's motion over 16 years (Barnard, 1916). The background stars are moving as well, but their motion is not as discernible over short time periods.

may seem to have strayed from our original topic of star clusters, but the point is that all of Astronomy is at its core an exploration of the Universe in an attempt to understand its (and our!) evolution.

Although star clusters form in the same region and are held together gravitationally, over tens or hundreds of millions of years their stellar constituents will eventually drift apart from each other. The Pleiades, for instance, appears so tightly bound on the sky to us because it is still very young in terms of stellar lifetimes – only around 125 Myr old (Converse & Stahler , 2010) – and has not had time to disperse. This age represents only half that of the calculated relaxation time for the Pleiades (the time it will take for individual members of the Pleiades to have their motions significantly changed by interactions with the other members of the cluster). Further, depending on the types of interactions the Pleiades has with the Galactic tidal field (or the close passage of a giant molecular cloud), 75% of its stars may escape the cluster in the next 200 to 600 Myr (Converse & Stahler , 2010).

If we were around to observe the stars in the Pleiades in, say, a billion years, we would most likely no longer be able to find them by looking for a tightly bound cluster. We would still be able to find them, though, by looking for them in proper motion space instead of celestial coordinate space.[1] This is in fact what we find when we examine the proper motions of large numbers of stars in the night sky – overdensities in proper motion space which show stars that, although they are not necessarily clustered near each other in physical space, have very similar motions.

Here we define moving groups as dissociated star clusters that have maintained components of their initial velocities (Eggen, 1958). Members of moving groups are expected to be essentially the same age and have the same initial compositions (since they formed from the same cloud of gas). Identifying and studying moving groups helps form a more complete picture of stellar evolution and the dynamical evolution of the Galaxy. Because of the large timescales involved in the evolution of galaxies, we are forced to observe much more than a single star or even cluster. Instead, we must piece together many different stars or clusters at different stages in their evolution in order to find out how they formed and how they got to where they are now. In order to study these moving groups, we are going to need two things: a large amount of data on stars and complex tools to analyze this data. Our large amount of data comes from a space based telescope and our complex tools for analysis come from a set of codes written by Dr. Jeff Andrews in the Python programming language.

On December 19, 2013 the European Space Agency launched the *Gaia* spacecraft 1.5 million km to the second Lagrange point of the Sun-Earth-Moon system (Gaia Collaboration , 2016). The Gaia mission was intended to dramatically improve upon the mission of its predecessor, Hipparcos, which collected detailed astrometric observations.

A key difference in the two missions is that Hipparcos searched for 118,000 predefined targets, while Gaia performs an unbiased study of the sky, picking up all objects in its field of view with limiting magnitudes in the G band of light between G=21 and G=3. On April 25, 2018, Gaia Data Release 2 (DR2) was made available to the public with precise astrometric data for 1.3 billion stars.

2 THE CODE

In order to analyze the astrometric data for these 1.3 billion stars, we employ a code developed by Dr. Jeff Andrews in the Python programming language (Andrews et al., 2017). This code was originally developed to identify binary star systems by comparing the kinematics (pmra, pmdec, and parallax) of stars from stars in GAIA DR2, but has been modified to search for stellar associations. These modifications employ the same base algorithm but go a step further to collect these binary pairs into larger stellar associations. For every pair of stars within our chosen search radius (which we can set for each run) the code calculates the probability that each pair constitutes a true binary. By comparing the proper motions of each star against a computer model formed by generating 10^4 binaries with different separations, eccentricities, and orientation, we are able to find the likelihood that the difference in a pair's proper motion is consistent with binary motion (Andrews et al., 2017). From here, we then set a threshold probability for pairs of stars (usually above 99%) and collect a network of all the pairs that pass our threshold. These networks constitute our potential stellar associations, and it is from here that we can begin to investigate the validity of the code's output.

3 TESTING AND CALIBRATION

Our first step in this project was getting the code up and running on our computers and making sure we were getting the output we wanted. The easiest way to do this was to set our search parameters to something that was well known and studied. For each run, the code requires the search parameters ra, dec, parallax, and search radius (in degrees). This automatically reduces the number of stars

[1] Positions of objects on the sky are usually given in celestial coordinates – that is, in terms of declination and right ascension, which correspond to latitude and longitude, respectively. Proper motion is then the amount that an object appears to move across the sky in right ascension, pmra, and in declination, pmdec.

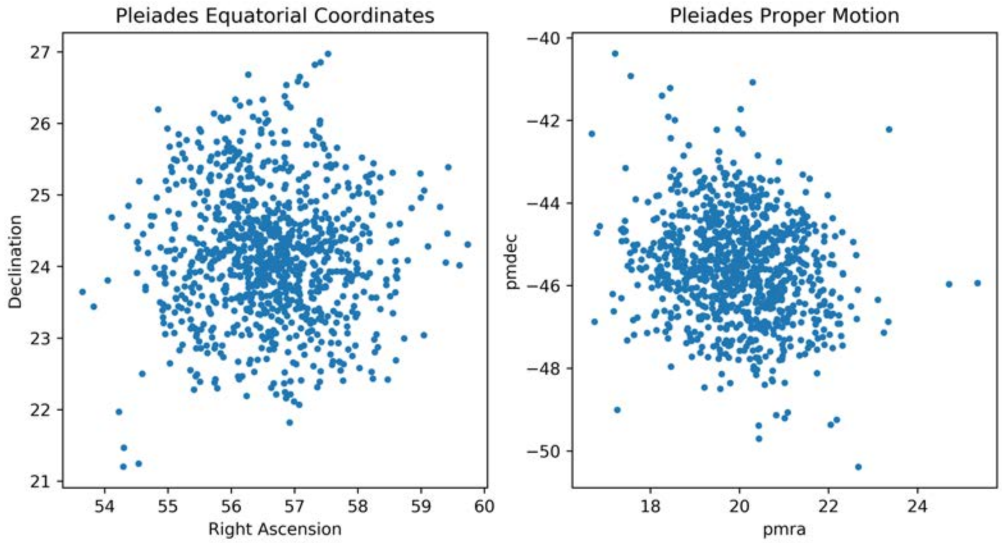

Fig. 3. Plots of identified Pleiades members in equatorial and proper motion space.

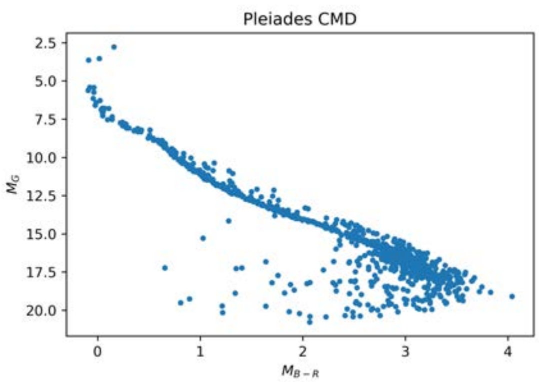

Fig. 4. Color magnitude diagram for 1,003 identified Pleiades members.

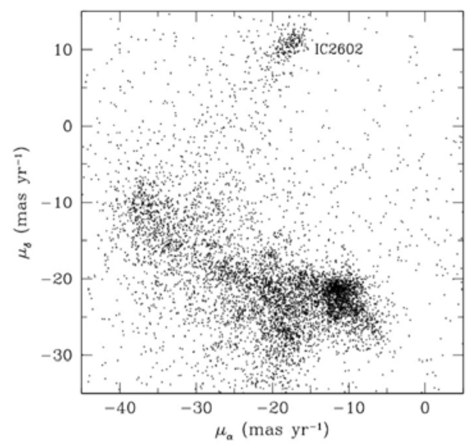

Fig. 5. Plots of stars in vicinity of Scorpius Centaurus from Luhman & Esplin (2020). Overdensity near -20, 10 is Upper Scorpius.

the code has to compare, allowing us to conduct searches without having to parse the entire 1.3 billion stars for each run. We are also able to set constraints on certain properties of the code, such as how similar the proper motions of the stars need to be or how far apart on the sky they can appear from each other to qualify as matches.

Pleiades

We first tested our code against was the well studied Pleiades open cluster. We centered our search about ra=56.75° and dec=24.12° with a search radius of 5° and parallax limits of 6–9 milliarcseconds and identified 1,003 members as having similar enough kinematics to constitute a stellar association. The plot on the left panel of Figure 3 shows the identified Pleiades members in right ascension and declination (as they appear to us on the sky) while the plot on the right panel shows them in proper motion space. These results are consistent with the accepted value of 1,256 members for the Pleiades (Converse & Stahler , 2010). The color magnitude diagram in Figure 4 also shows an extremely well defined main sequence for the Pleiades. One may also note how there almost appears to be two lines moving diagonally, with the thinner line seeming to rest above the denser, more well defined line. This "second" line is actually just showing close binaries – stars that are so close to each other in space that we are unable to differentiate their light from one another. Instead of seeing two distinct stars, their light is blended together so that our instruments (or our eyes!) believe we are seeing just one bright star.

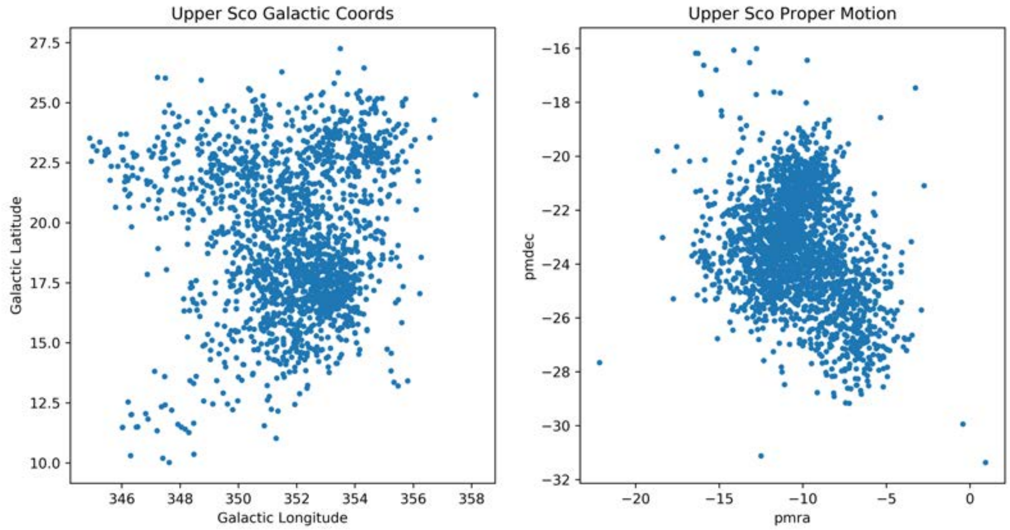

Fig. 6. Plots of identified Upper Sco members in galactic coordinate and proper motion space. Results in proper motion space are consistent with those identified by Luhman & Esplin (2020) in Figure 5.

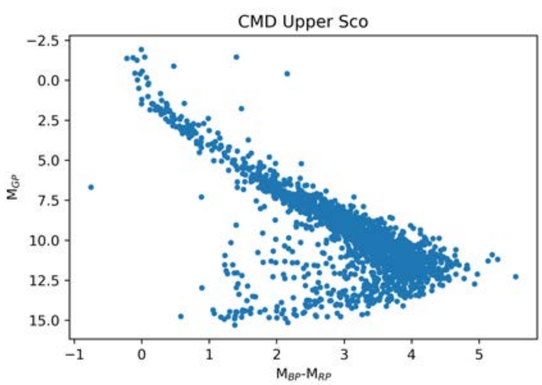

Fig. 7. Color magnitude diagram for 2,195 identified Upper Sco members.

Upper Scorpius

We then decided to test the code on Upper Scorpius, which is a subgroup of the Scorpius Centaurus OB Association along with Upper Centaurus-Lupus and Lower Centaurus-Crux (Wright & Mamajek, 2018). Scorpius Centaurus is the closest OB association to the Sun. OB associations are conglomerates of hot, massive stars that have very short lifetimes (10s of Myrs or less) and thus are by definition young star clusters. Upper Scorpius contains around 2,100 stars with their median age being 11 Myr (Luhman & Esplin, 2020). We centered our search about ra=241.9° and dec=-24.4° with a search radius of 15° and parallax limits of 5.5-8.0 milliarcseconds and the code found a cluster of 2,195 stars, consistent with the Luhman & Esplin (2020) estimate of 2,100 stars. Figure 6 shows these 2,195 in galactic coordinates and proper motion space. Compare this with Figure 5 from Luhman & Esplin (2020) and you can see the dark clustering region in the same proper motion space. The color magnitude diagram in Figure 7 also shows a main sequence of stars that is similar to that of the Pleiades, though much thicker. This thickness is due to the youth of the cluster, as most stars of Upper Scorpius are so young that they have yet to fully mature into their spot on the main sequence.

4 SEARCH FOR NEW ASSOCIATIONS

After using the Pleiades and Upper Scorpius stellar associations to calibrate the code, we decided to move forward with trying to find something new. From this point onward, we would no longer be using the code to find clusters or moving groups that we knew had already been identified, but searching for new groups altogether. We centered our first search about a point 90° offset from the galactic anticenter (GA90,) with coordinates at ra=86.50° and dec=28.76° with a search radius of 5° and parallax limits of 2-10 milliarcseconds. The results are shown in Figures 8 and 9.

The overdensities shown in Figure 8 along with the well defined main-sequence in the color magnitude diagram in Figure 9 point towards the identification of a legitimate cluster. In proper motion space these 266 stars (blue in both figures) group together tightly, telling us that they are very likely either a moving group or open cluster. Although the line between open cluster and moving group can sometimes be blurry, the fact that these stars only spread out over a 5 degree region of the sky (galactic coordinates) indicates that they have likely not drifted far enough apart from each other on the sky to no longer be considered an open cluster. Figure 9 shows a thin main sequence (more similar to that of the Pleiades than to that of Upper Scorpius), likely indicating an older, more mature cluster. Recall that the Pleiades' main sequence was thinner

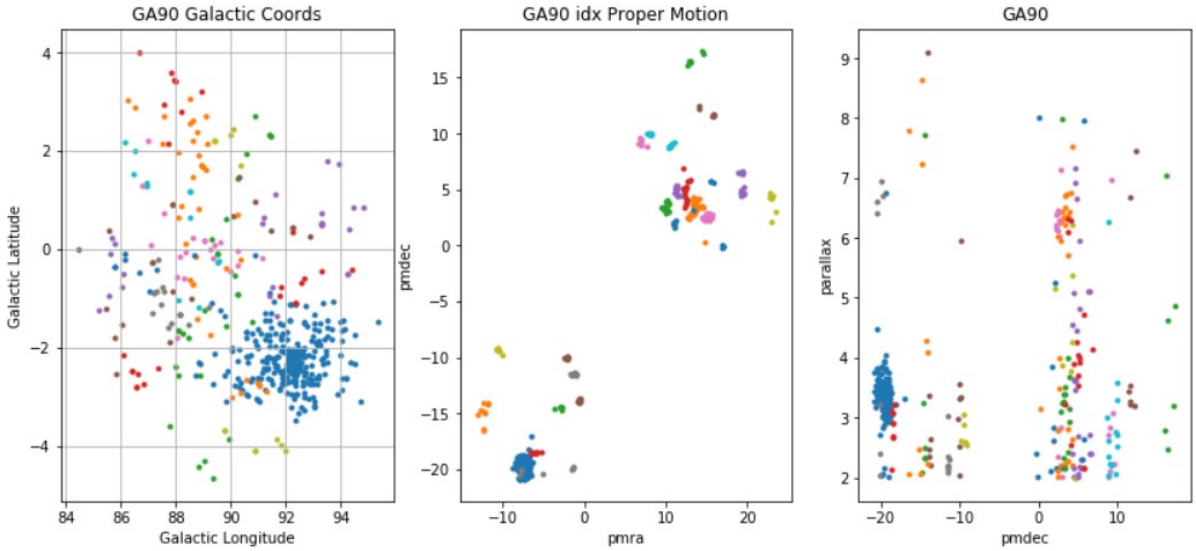

Fig. 8. Plots of various clusters identified in 5 degree radius search centered on region 90 degrees offset from galactic center.

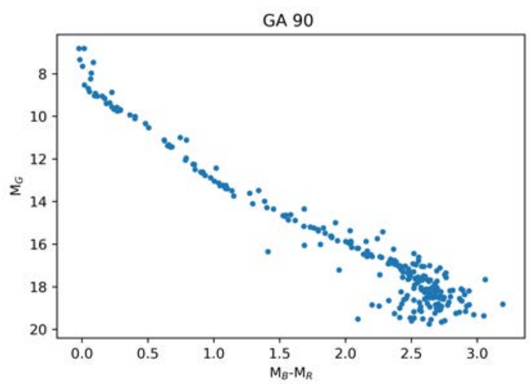

Fig. 9. Color magnitude diagram for the 266 stars identified in Figure 8.

Fig. 10. Messier 39 Open cluster

because of its older age (approx. 100 Myr) compared to that of Upper Scorpius (approx. 10 Myr). Our next step with this new group was to search the literature to see if it was a known stellar association. Its relatively large size (266 stars) made us believe it was unlikely that it had not been identified before, and we found that to in fact be the case. The cluster we had identified is Messier 39, an open cluster in the Cygnus constellation, shown in Figure 10. This cluster has an estimated age of 200-300 Myr, which explains the thin main sequence that we observe.

5 CONCLUDING REMARKS

Although we have yet to identify any new associations, we have proven the accuracy of the code developed by Dr. Andrews and are continually working towards improving our search parameters for the most accurate and efficient searches of the sky. We are confident that even if we are unable to discover any entirely new associations, this code is powerful enough to improve existing membership catalogs with higher levels of confidence than can be offered by many other codes developed for similar purposes.

REFERENCES

Andrews, J.J, Chanamé, J., Agüeros, M. A. 2017. MNRAS, 472:675–699
Barnard, E.E. 1916. Astron J, 29:181–183
Converse, J.M, Stahler, S.W. 2010 MNRAS, 405:666-680
Eggen, O.J., 1958 MNRAS, 118:154-159
Ehser, A., Borg, G., Pernicka, E. 2011 EJM, 23:895-910
Gaia Collaboration. 2016 A&A, 595:A1
Luhman, K.L., Esplin, T.L. 2020 Astron J, 160:44-82
Wright, N., Mamajek E. 2018 MNRAS, 476